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A POLICY MODEL OF USAF AIRCRAFT OPERATIONAL RELIABILITY

Laurence A. Johnson, Captain, USAF
Edward R. Laase, GS-12

LSSR 12-79B

UNITED STATES AIR FORCE
AIR UNIVERSITY
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Wright-Patterson Air Force Base, Ohio

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The USAF does not have a well defined methodology for top level policy managers to make policy decisions concerning the operational reliability of aircraft weapon systems. This thesis was directed at creating a methodology through a computer simulation model. System dynamics provided the framework to construct the model, and DYNAMO was used for computerization. The elements of integrated logistics support were combined in the model into four key support parameters of personnel, supply, equipment and facilities. The model was designed to measure the total USAF capability in terms of these four parameters. The key measure being the capability available for surge requirements after normal operations have been accomplished. The model includes the effects that research and development have on improving this capability through technology, resulting in increased maintainability and inherent reliability. One use of the model was to identify those variables that require better measurements to determine the actual capability of USAF aircraft weapon systems. It is hoped that this model will be of use to policy makers within the Air Force as an experimental tool to determine the possible impacts of changes in policies.

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A POLICY MODEL OF USAF AIRCRAFT OPERATIONAL RELIABILITY

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

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September 1979

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COMMITTEE CHAIRMAN

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CHAPTER I

INTRODUCTION

Reliability is a fundamental characteristic of a system and is expressed as the probability that the system[1] will perform its intended function for a specified period of time under stated conditions (4:63). This definition, however, does not explain the many facets of the total system that influence system reliability. The term reliability used in this thesis cannot simply be defined as an isolated concept of equipment failure. This concept must be broadened to consider the effects that other system parameters have on reliability. For example, how do training, maintenance concepts, design, and technology affect reliability? How do combinations of these system parameters affect reliability? Most importantly, where can management place emphasis in order to achieve an increase in the reliability of the total system? The purpose of this research is to provide a much broader concept of reliability normally given in technical reports. The concept will be expanded by constructing a model which simulates

---

[1] A system is a collection of parts organized for a purpose. In this thesis, a system will refer to a complete system, unless otherwise noted in the text. The concept of the system will be operationally defined in subsequent chapters.

the effects that the dynamic behavior of a system has on the flying capability of the Air Force.

Problem Analysis

In the fiscal year 1975 Annual Defense Department Report, Secretary of Defense Schlesinger noted that the improvement of reliability of new weapon systems was receiving increased management attention within DOD (18: 229). For example, suitable tools and techniques for determining reliability are required by managers to successfully deploy new weapon systems that meet mission requirements. Mission requirements for each system are initially defined in broad terms by the Mission Element Need Statement (MENS). When making trade-off decisions early in the acquisition phase, the manager must be able to compare the overall reliability of a weapon system with the cost to operate and support that system (7:2). However, existing models used to compare operating and support (O&S) costs and reliability do not provide realistic cost estimates (5:2).

A March 30, 1976, letter from the Senate Appropriations Committee, requested the General Accounting Office (GAO) to determine if there was any method to measure improved performance of a weapon system as it affects support costs and manpower requirements (19:iv). The GAO recommended that the Air Force and Navy explore the

possibility of developing reasonable criteria and data systems for measuring and evaluating the results of the programs for improving maintainability, reliability, and life cycle costs (19:A-2). The GAO identified a need for a model that can determine the cause-effect relationship between management decisions and the reliability of a weapon system. Current management practice is to determine reliability through engineering models such as the Duane Reliability Growth Model (11:38).

J. T. Duane of the General Electric Motor and Generator Department found that an ongoing test, analysis, and correction program would provide a continually increasing Mean Time Between Failure (MTBF).[2] The Duane Model is an empirically derived relationship of cumulative failure rates versus cumulative test hours. When this relationship is plotted on a log-log scale, the data points fall along a straight line. Duane and others have confirmed this relationship for many diverse types of equipment (11:38-40).

The Duane Model, the most widely used reliability growth model (11:38), pointed out the existing limited notion of reliability. The Duane Model did not consider the complex interactions among the many factors that determine the reliability of a system.

---

[2]MTBF is one commonly used measurement of the reliability of a piece of equipment.

It has become a common occurrence within DOD to expect field reliability of new weapon systems to be less than the reliability predicted by contractors and/or reliability test results (12:68). Available data indicated that field MTBF is often only one-tenth of the specified MTBF (10:30). The contractor's predicted reliability of a system using existing models apparently cannot relate to the actual field reliability observed. The system reliability did not meet the predictions because reliability has not been understood or managed as a system. All of the factors that determine the system reliability were not considered in the design of the model.

Robert A. Singer, in a Defense System Management Report, stressed the point that the most serious disadvantage of existing models was the current unavailability of accurate measurements depicting the relationships between performance goals with actual performance achieved (17:19). Also, some critical assumptions used in current models must be replaced by more realistic representations of the dynamic nature of systems. When considering reliability the models assumed random failure only. No provisions were made for the implications of corrosion, fatigue, and wear-out. Design values were used rather than actual field failure rates. Secondary failures due to extrinsic causes were ignored, even though the failures required maintenance actions (17:22-23). The problems of incorrect part

replacements, false fault alerts, and intermittent failures were not considered (17:73). The effects on reliability of transportation, spares policy, training, quality of technical data, and support equipment were also not included in the available models.

Most models assumed that an improvement in reliability translates directly into changes in other system parameters (for example, fewer spares, fewer maintenance actions). It can be shown that an improvement in reliability may actually dictate fewer maintenance actions. Fewer maintenance actions might mean fewer maintenance personnel. However, unless manpower assignments are reduced to match the predicted requirement, none or only a small fraction of this predicted savings in manpower will come about. In some situations manpower reductions may not even be possible because of policy considerations. An example is a Navy ship where peak manpower requirements for critical functions, such as damage control, assumed there were fixed levels of manpower available from other functions. Also, fewer maintenance actions may lower the proficiency of the maintenance personnel which could, in turn, cause a decrease in the reliability of the system (17:23).

The dynamic behavior of the relationships described in the preceding paragraphs must be understood, measured, and then incorporated into a model for accurate understanding of reliability. Using this model, managers can

determine where to apply available resources to achieve desired results.

Problem Statement

The variables which affect the reliability of an aircraft weapon system are not adequately understood by DOD managers.

Concomitant with the major problem is a secondary problem. Management has not developed adequate tools to measure or define the interrelationships between reliability and the elements of the system which determine reliability.

Background

Literature Review

The available literature on reliability was divided into two main groups. Figure 1-1 summarizes this literature.

One group dealt strictly with engineering studies done to aid in designing and predicting reliability of new systems. This thesis is about the management of reliability and does not consider specific engineering reliability design techniques. Consequently, reliability engineering studies were not included in this background section. However, the concept that improved design may increase the reliability of a weapon system is recognized and will be included in the model. The remaining literature considered reliability from a management viewpoint.

RELIABILITY LITERATURE

ENGINEERING RELIABILITY	MANAGEMENT RELIABILITY
Mathematical functions to predict reliability	Relationships among reliability, maintainability, O&S costs, acquisition costs
Reliability test results for specific components	Life cycle costs as a function of reliability
Reliability design	Design changes to increase reliability
	Trade-off studies to determine optimum reliability

Fig. 1-1. Summary of Reliability Literature

The prevalent theme in the literature concerning management of reliability was expressed by Eldridge P. Eaton. In his article, "Let's Get Serious about Life Cycle Costs," he stated that reliability was a design controllable characteristic of a system (7:2) and that "good" managers must consider the relationships among reliability, maintainability, O&S costs, acquisition costs, spares, personnel, and all other logistics factors and mission requirements (7:3). These relationships were usually presented in terms of total life cycle costs of a system.

The management of any system is a continuous iterative process. Through system development, design changes in various subsystems are proposed while the accuracy of cost estimates as well as performance and

effectiveness estimates are being improved. To manage a program by meeting the performance and economic goals, a manager must have a timely feedback of current information on the cost and performance estimates of all proposed subsystem changes (1:65).

Absent in the literature was a rigorous methodology for conducting the analysis of the complex system interactions. Eaton provided a description of what "good" DOD managers are expected to do:

> There is an infinite number of possible trade-offs based on selected logistics alternatives. Each system, because of its difference from other systems, contains its own unique solutions. However, the trade-off processes should be identical: creating a balanced design, which incorporates the objective evaluations between intrinsic and extrinsic system characteristics, to produce a system that has acceptable operational capability and the readiness required at an affordable and optimal LCC [7:11].

This limited process expressed by Eaton does not provide substantial help to a manager trying to choose from an infinite number of trade-offs. Eaton's statement, however, does indicate that managers are beginning to understand the complex interrelationships they must deal with.

J. W. Forrester identified another difficulty managers have when trying to understand complex interactions. Forrester believed that the intuitive judgment of skilled investigators is unreliable in anticipating the dynamic behavior of a simple system of five or six variables. This

situation exists even when the complete structure of all the parameters of the system is known (8:99).

The difficulty in dealing with complex interactions or choosing from an infinite number of trade-offs, indicates managers cannot perform without some form of assistance. One form of this assistance is the development of a formal model which portrays the basic system structure the manager is trying to understand. System dynamics provides a methodology to create this formal model which can be used by the managers controlling the system. The system dynamics approach is to understand the structure of the system through literature reviews, interviews with people familiar with the system, and specific quantitative studies where necessary. From this rudimentary understanding of the system, a formal model is developed in the format of causal loop diagrams. The causal loop diagrams show the cause and effect relationships between the variables in the system. The model is then exposed to criticism, revised, and exposed again in an iterative process until a useful model is developed. The causal loop diagrams still only provide the manager with an intuitive understanding of the forces that cause system behavior. A mathematical formulation of the relevant variables is required to determine the probable consequences of proposed policies. A computer simulation model can be developed from this mathematical model (15:5-6). Roberts stated that, "Computer simulation is one

of the most effective means available for supplementing and correcting human intuition [15:6]."

This computer simulation model is not a perfect representation of the actual system making better decisions than people can. It is a tool which managers and policy makers can use to experiment with proposed changes prior to actual implementation. Unlike mental models that most people use to guide their actions towards a goal, the computer model is comprehensive, unambiguous, flexible, and subject to rigorous manipulation and testing (15:5-6). The detailed methodology on how systems dynamics will be used to develop the computer simulation model in this thesis is contained in the next chapter.

Described in the remainder of this chapter are some examples of existing models and the limitations of these models. The ability of systems dynamic models to overcome these limitations will be briefly discussed. The research objectives and research questions derived from the problem statement will then be presented. The chapter will conclude with the basic premise of the system dynamics technique.

Review of Existing Models

Computerized mathematical models are available to assist DOD managers in dealing with large numbers of variables when making decisions about reliability. The most

common examples are LCC models that use the reliability of a system as one of many inputs. The U.S. Army Air Mobility Research and Development Laboratory has developed the Aircraft Reliability and Maintainability Simulation Model (ARMS).

The ARMS was developed as a management tool which permits observation of the impact of a proposed maintenance concept prior to implementation. The model is used to simulate aircraft operating in user defined operational scenarios. It is designed to allow the user flexibility in defining aircraft components with their associated failure rates and repair requirements, and in defining necessary resources such as ground equipment. The ARMS model can be applied throughout the life cycle of an aircraft system from the conceptual phase through the developmental, and during the operational phase. It can be used to determine the system level impact of changes in reliability and maintainability parameters at the component level, to determine the effectiveness of alternative maintenance concepts, and to determine the optimum mix of maintenance resources (9:7).

The Logistics Management Institute (LMI) proposed to determine the relationships among system and subsystem reliability and life cycle costs. This model used three principle model parameters. These are: (1) cost of system downtime (costs to achieve constant mission requirements); (2) design, development, test, acquisition, and program

management costs associated with achieving reliability; and (3) maintenance and support costs affected by subsystem reliability (17:8).

Limitations of Existing Models

The Arms model and LMI model, as did other models studied, used reliability as an input required to determine other system parameters, such as availability, manpower requirements, or LCCs. Most significantly, these computer models did not include the closed-loop information feedback system. By not including this information feedback system, the model failed to capture the system structure that was being studied, and did not show how other system parameters affected reliability. A closed-loop information feedback system is generated whenever an action affects the environment, and that action subsequently influences future decisions about the environment (8:14).

Additional limitations in computer models were identified by Joint AFSC/AFLC Commander's Working Group on Life Cycle Cost. This group concluded that:

1. The models are too complex.

2. The requirements for input data frequently cannot be fulfilled.

3. The models are not sensitive to the relationships between design and performance.

4. The models are not sensitive to failures caused by the increasing age and wear of a system (10:8).

Improvements are being made in computer models, but all of the limitations identified above still exist (7:6).

The final limitation to be discussed is the failure of existing models to consider how policy and management structure changes may affect a system. Too often, policy and management considerations are brushed aside as given or preconsidered assumptions and are not identified as variables that may have the greatest effect on system behavior (7:6-7).

The next section will provide insight into some of the capabilities and techniques of system dynamics by briefly describing how properly constructed system dynamics models can correct the deficiencies of existing models. Managerial Applications of System Dynamics by Roberts contains examples of system dynamics models that have been implemented in a variety of situations.

System Dynamics Modeling

Including excessive detail which results in a highly complex model can be a serious problem in a system dynamics model, just as it is in existing models. Variables are often left in models to avoid discriminating thinking about whether or not the variables actually contribute to system performance. Some detail, even if it does not affect system

performance, can be justified as providing an apparent reality to the model. This apparent reality makes the model easier to explain to the managers who will use the model. The skill that the builder brings to the modeling process determines whether a model becomes too complex or oversimplified (8:453).

A system dynamics model does not require large quantities of statistical data to be effective. In system dynamics, the model is based upon actual system structure and is subsequently used to determine what formal data needs to be collected (8:57). It can usually be determined if the actual value of the data must fall within a certain range. Estimates of the numeric values to be used in the model are made. The model is then used to determine the sensitivity of the system to changes in these values. Often the model is relatively insensitive to changes in values within the estimated range, and expending resources to refine the estimate would be unjustified. If the model shows that the entire qualitative behavior of the system depends on a numerical value that was estimated, then this value must be measured with adequate accuracy. The main point is that a mathematical model should be based on the best information available, just as management decisions are based on the best information available. The design and use of a model, however, should not be postponed until all pertinent parameters have been accurately measured.

Values should be estimated when necessary to enable the model to be put into productive use (8:58). Forrester summarized his views on data as follows:

> Dynamic models will be based primarily on our descriptive information already available, not on statistical data alone. Observation of and familiarity with a system will reveal actions, motivations, and information sources that cannot be discovered through historically available quantitative measures [8:130].

A system dynamics model must describe the cause-effect relationships that exist in a system (8:67), such as the relationship between design and performance parameters. These cause-effect relationships can be mapped onto a system dynamics model through a structure of levels, which are interconnected by controlled flows (8:67). The levels are accumulations within the system (8:68). Examples of levels within an aircraft weapon system are the number of trained crews available to operate the aircraft in the inventory, the number of aircraft in the inventory, or the amount of flying hours available to fly these aircraft. Controlled flows emerge from these levels. The controlled flows are made up of the flows that transfer the contents of one level to another level and the decision functions that control the rates of flows between levels. The rates correspond to an activity within a system, while the levels measure the state to which the system has been brought. The decision functions are the policy statements that determine how the available information about the system state

(a level) leads to a decision (a rate) resulting in a change to the system (a flow from one level to another) (8:68-69).

For example, there may be twenty crews (level) available to fly twenty aircraft. Policy may require two crews for every aircraft. This policy leads to a decision (a rate) which causes additional crews to be trained (a flow or activity) until forty crews are available (a new level).

A system dynamics model is a network of these levels and rates which are interconnected by an information network. The information network is also a sequence of alternating rates and levels (8:71). System dynamics model structure is simple and straightforward. The structure permits a one-to-one correspondence between the model and the system being represented (8:131).

System dynamics is aimed at modeling dynamic systems which tend to evolve over a period of time (14:xx). Aircraft accumulate more hours and more sorties which illustrates a type of time-varying behavior, which can be modeled using the system dynamics concepts of levels and flows already explained (8:50). Aircraft in maintenance can be thought of as a level into which aircraft flow after flying a mission. The rate at which these aircraft flow into maintenance is a function of how many sorties are

flown. As more sorties are flown, more aircraft flow into maintenance.

The last deficiency of existing models concerns the absence of specific ability to capture the policies and structure of the system. By failing to capture the structure of the system, these models failed to reproduce or predict the behavior characteristics of the system. Characteristics such as stability, oscillation, growth, and general time relationships between variables are required to understand the system and to make changes for system improvement (8:54).

In general, system dynamics modeling has two objectives:

1. Explaining the system's behavior in terms of its structure and policies.
2. Suggesting changes to structure, policies, or both, which will lead to improvement in the behavior [6:19].

Thus a system dynamics model is created to enhance the understanding of the policy and structure of a system, the very two elements that are left out of most other models.

Throughout this chapter, basic concepts and techniques of system dynamics have been introduced to show how system dynamics overcomes many of the problems faced by managers trying to manage complex organiztions. It is appropriate now to summarize these concepts and techniques by providing the basic premises of system dynamics modeling.

1. Decisions in management and economics take place in a framework that belongs to the general class known as information feedback systems.

2. Intuitive judgment is unreliable about how these systems will change with time, even with good knowledge of the individual parts of the system.

3. Model experimentation is now possible to fill the gap where judgment and knowledge are weakest--by showing the way in which known separate system parts can interact to produce unexpected and troublesome overall system results.

4. Enough information is available for this experimental model-building approach, without great expense and delay in further data gathering.

5. The "mechanistic" view of decision making implied by such model experiments is true enough, so that the main structure of controlling policies and decision streams of an organization can be represented.

6. Systems are constructed internally in such a way that the system creates many of the troubles that are often attributed to outside and independent causes.

7. Policy and structure changes that will produce substantial improvement in system behavior are feasible and system performance is far from what it can be. Initial system design changes can improve all factors of interest without a compromise that causes losses in one area in exchange for gains in another (8:13-14).

Summary

In this background section, it was shown that the concept of reliability as part of a total system is only beginning to be understood by managers. The limitations of existing models do not allow managers to effectively control the reliability of a system. System dynamics does provide a framework whereby the reliability of a system can be analyzed, and improvements can be made to enhance a system's reliability. The research questions derived from the problem statement and background are presented next.

Research Objectives

The objective of this research is to develop a model of the dynamic system determining the reliability of aircraft weapon systems. Specific objectives are:

1. To identify the most significant internal and external forces affecting reliability of an aircraft weapon system.

2. To identify the cause-effect relationships and information feedback loops that control reliability.

3. To construct a model which represents the forces, relationships, information flows, and decision policies of the reliability system.

4. To develop management policies which make possible more effective control of reliability.

5. To provide knowledge that data collection designers need to measure reliability.

6. To provide an improved conceptualization of reliablity for other researchers to use to define the reliability system.

Research Questions

1. What are the relationships between reliability and other components of a system which affect the total reliability of a weapon system?

2. Can a conceptualization of the interrelationships between the reliability of a system and the other components of the system be developed and used as the basis for a mathematical computer simulation model?

3. Can the developed model function as a management tool, whereby, managers can determine the effect that proposed changes in other system components have on reliability?

Summary

In this chapter a new concept of reliability has been advanced. The research was designed to refine and present this concept through the development of an operational model, which can be used by managers. An analysis of the current situation concerning reliability was presented. This analysis led to the problem statement that the variables, which affect the reliability of aircraft weapon

systems are not adequately understood by DOD managers. The background section discussed some current management thinking about reliability. This section also identified the difficulties managers faced when trying to deal with complex interactions, such as interactions between reliability and other components of a system. A review of existing models pointed out both capabilities and limitations. System dynamics was introduced and suggested as a technique which would be a valuable tool to aid managers in overcoming many of these limitations found in existing models. The chapter concluded with the research objectives and research questions.

In Chapter II, a methodology of the system dynamics paradigm will be presented. Each individual procedure will be explained, and an example will be provided. Chapter III will present the construction of the system structure through the use of causal loop diagrams. In Chapter IV, flow diagramming and DYNAMO equations will be presented along with explanations of how the diagrams and equations were formed and why they are included in the model. Chapter V will contain an analysis of two management concepts and show how these concepts affect the operational reliability of the aircraft weapon system.

CHAPTER II

METHODOLOGY

Introduction

Described in this chapter is the system dynamics paradigm as applied to the analysis of reliability. The first section discusses model design procedures. Detailed explanations of each of these procedures will follow, describing how the model of aircraft weapon system reliability will be developed. Validation and analysis of this model will then be covered. In this section some of the limitations of the validation process will be discussed. The chapter will conclude with a final section summarizing this chapter and outlining the direction the final chapters of the thesis will follow.

Model Design Procedures

To construct a dynamic simulation model of the reliability of a weapon system, six steps have been identified.

1. Identify the system and the sectors of the system to be studied. Determine if a dynamic system oriented investigation is warranted.

2. Draw causal loop diagrams showing the interaction of the system's variables.

3. Develop a mathematical model of the system by:

a. Converting the causal loop diagrams into detailed flow diagrams and;

b. Converting the detailed flow diagrams into DYNAMO mathematical equations.

4. Generate over time, through the use of the computer, the behavior of the modeled system to validate that the model reasonably represents the system under study.

5. Conduct simulation experiments to determine those variables within the system that are sensitive to changes.

6. Incorporate redesigned system parameters into the model, followed by computer runs, to determine the effect the changes have on the system behavior. From these simulation experiments, recommend changes to the system that improve system performance or identify areas that need additional study (14:xx-xxi).

What follows are brief descriptions of the stages of the system dynamics process as they relate to the reliability of a weapon system.

Identify the System

The first stage in developing a system dynamics model is to identify the system and determine if a system-oriented investigation is warranted. The fact that the reliability of a weapon system deserves a system dynamics

study has already been discussed in Chapter I. System sectors are identified to provide a conceptual framework through which the model structure is developed (6:24). Determining the appropriate system sectors to include in the model requires considerable analysis and the final decision of what should or should not be included in the system sectors rests with the model builders. The sectors selected for this model are Maintenance, Operations, and Research and Development. Relationships between and within sectors are defined by interconnected networks of material, requirements, money, personnel, capital equipment, and information which flow among sectors. Figure 2-1 is an example of the overall system sector diagram illustrating how the network of flows connect the sectors.

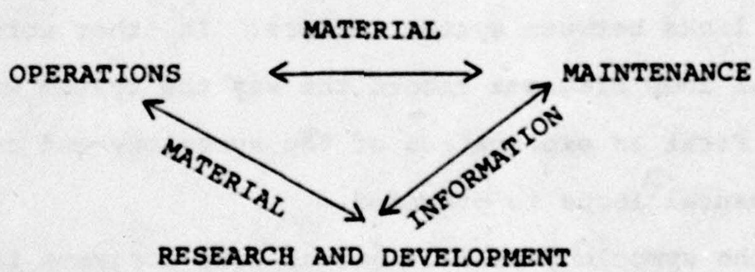

Fig. 2-1. System Sector Relationship

The Operations Sector controls the operational aspect of the reliability model. In the Operations Sector, aircraft are scheduled and flown in terms of sorties. These sorties constitute the operational reliability of the aircraft weapon system. The activity in the Operations

Sector generates aircraft for the Maintenance Sector. The Maintenance Sector services and restores the aircraft to operational status, and these aircraft are again available for operational use. The Research and Development Sector provides aircraft with improved reliability and maintainability through increases in its technological base. The sector descriptions and interactions will be explained in greater detail in the chapters on causal loops and flow diagram analysis.

Causal Loop Diagrams

Causal loop diagrams extend the concepts made explicit in the sector diagrams by identifying the variables and the pairwise relationships of these variables within system sectors. The causal loops also provide the relationships or links between system sectors. In other words, the causal loop diagrams record the way the system works (6:63). First an explanation of the symbology and construction of causal loops is provided.

The symbology used in causal loop diagrams is straightforward. Arrows identify the causal link with the direction of the arrow indicating the direction of the cause-effect relationship. The polarity of the causal link is indicated by a + and - sign. The + indicates a positive link, and the - indicates a negative link. The polarity is determined by considering the effects a change in the

variable at the tail of the arrow would have on the variable at the head of the arrow. The rule is: if the head variable changes in the same direction as the tail variable, the link is positive; if the head variable changes in the opposite direction of the tail variable, the link is negative (6:63). Figure 2-2 provides an example.

Aircraft Availability	$\xrightarrow{+}$	Aircraft Sorties	Positive Link
Aircraft in Maintenance	$\xrightarrow{-}$	Aircraft Availability	Negative Link

Fig. 2-2. Causal Link Example

By combining causal links, complete loops are formed. The polarity of the loop is determined by counting the number of negative pairwise relationships. An even number of negative links or no negative links produces a positive loop. Figure 2-3 provides examples of causal loop diagrams.

The negative causal loop is interpreted as follows. As the maintenance on the aircraft goes up, the availability of the aircraft goes down--a negative link. As the availability of the aircraft goes up, the operational use of the aircraft goes up--a positive link. There is one negative link which means the causal loop has negative polarity. This causal loop indicates the more the aircraft are flown the more maintenance is required and the less the aircraft are available for use.

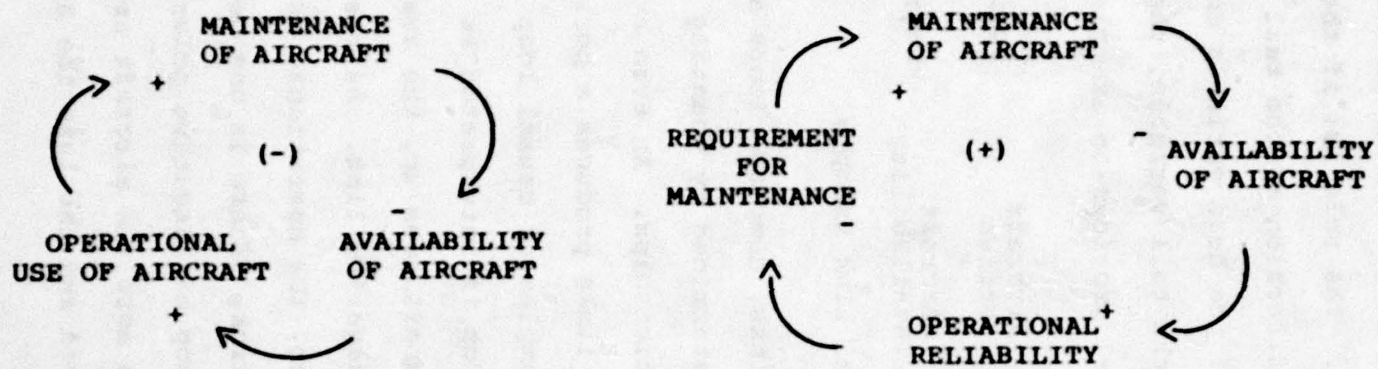

Fig. 2-3. Causal Loop Example

The first link in the positive causal loop is interpreted the same as in the negative causal loop. New variables have been included which changed the polarity of the causal loop. As the availability of aircraft goes up, the operational reliability of the aircraft goes up, a positive link. As the operational reliability goes up, the requirement for maintenance goes down, a negative link. As the requirement for maintenance goes up, the maintenance of aircraft goes up, a positive link. There are two negative links which means the causal loop has a positive polarity. This causal loop indicates the more operational reliability the less maintenance required which results in more availability and more operational reliability.

Negative loops contain a control mechanism which attempts to regulate the system (6:40). Positive loops tend to promote uncontrolled growth or decay (6:38-39). Although the causal loop diagram is very useful for model building, it is necessary to draw a detailed flow diagram in the programming stage (6:113). These flow diagrams are discussed in the following section.

Flow Diagrams

The derivation of the flow diagramming process comes from the study of the system and is based on the causal loop diagrams previously discussed. The symbology used in flow diagrams is depicted in Figure 2-4. The flow

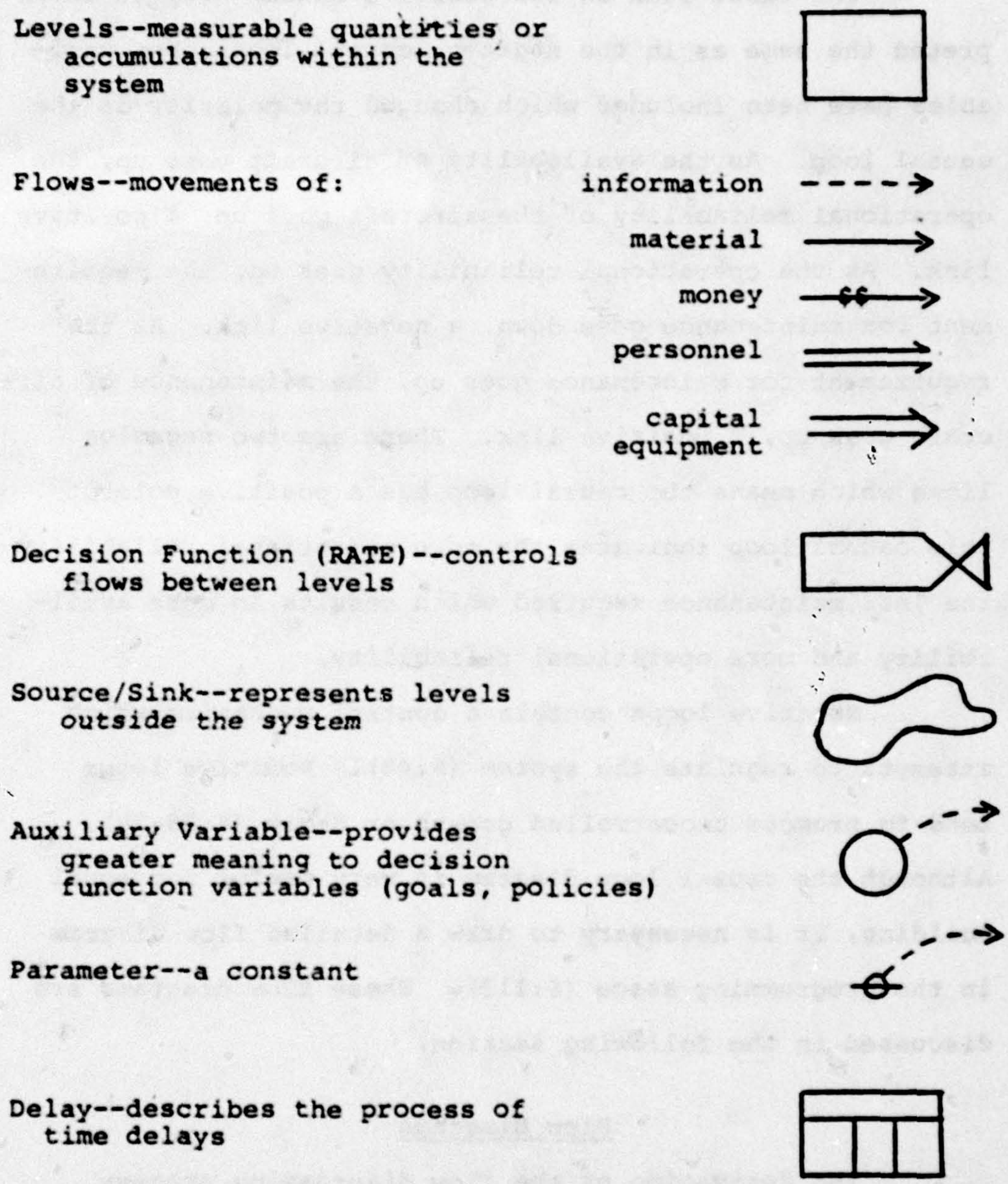

Fig. 2-4. Flow Diagram Symbols (8 :82-84)

diagram represents the concept of levels and rates explained in Chapter I. Figure 2-5 provides an example which shows how the level of aircraft availability (AA) is controlled by the aircraft repair rate (ARR). The aircraft repair rate is a function of the number of aircraft in maintenance (AM) and the aircraft repair factor (ARF). Various support factors enter this repair factor and will be explained in greater detail when the complete flow diagram analysis is presented. The mathematical equations are derived directly from the flow diagrams.

Equations

The developed equations will become the basis for the DYNAMO computer simulation model of reliability. The five classes of equations in DYNAMO are level, rate, auxiliary, supplementary, and initial value. Level, rate, and auxiliary equations have time dimensions. Successive points in time are given the designations J, K, and L. The letter J denotes the past, the letter K denotes the present, and the letter L denotes the future. The notation used in the equations is similar to subscripting. An example from Figure 2-5 shows a level at the present time (AA.K). Levels have only a single letter as a time suffix because the values of levels are calculated at separate instants of time. Rates, which define the flows between levels, use two letters to denote the flow from the present time (K)

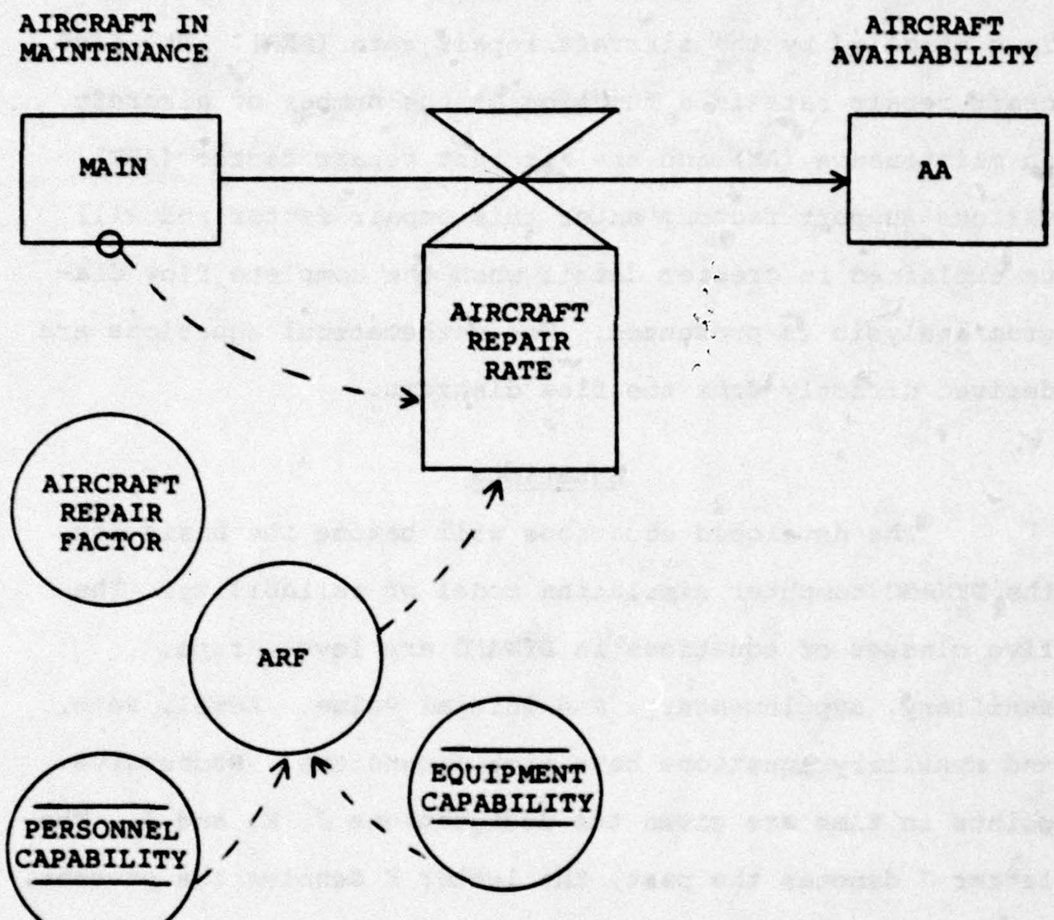

Fig. 2-5. Flow Diagram Example

to a future time (L), for example, ARR.KL. The ARR.JK symbol would be used to denote a flow from the past time (J) to the present time (K) (8:75-79).

The value of a level is a function of the prior level and rate at which the level is changing over the last time period (DT). For example,

AA.K=AA.J+DT*(ARR.JK)

Rates are normally functions of levels or auxiliary variables, but they can also be a constant value. For example,

ARR.KL=AM.K*ARF.K

where AM is the present level of maintenance and ARF is the aircraft repair factor, a fraction.

Auxiliary equations are used to decompose rate equations. The auxiliary equations allow the model to be kept in close correspondence with the actual system, since the auxiliary can be used to define the many factors that go into making up a rate.

Initial value equations define initial values of all levels (and some rates) that must be given before the first simulation run.

Supplementary equations are used to define variables which are used in the printing and plotting of model

values. Supplementary equations are not used in computing any values that affect the behavior of the system (8:79).

The equations developed for the simulation model are then verified. To verify the model, DYNAMO equations are compared to the flow diagrams and checked to ensure the equations do, in fact, represent the system as defined by the flow diagrams. Verification is performed to insure that the model is in fact what the modeler intended it to be. Having explained how the model is formulated, model validation and analysis will be discussed next.

Model Validation and Analysis

Model validation does not mean that the model will be proven. In this thesis, model validation is the process by which sufficient confidence is established to use the model for a particular purpose (6:181). Coyle stated ". . . there are no such things are models which are absolutely valid or completely invalid [6:182]." Validation of this model will consist of determining if the model reproduces system behavior.

Part of the validation has been accomplished through the knowledge gained from the literature review and the experience of the model builders. Statistical data were obtained from system effectiveness reports and combined to form an aggregate input into the model. This input represents as nearly as possible the operational

environment that the model builders are trying to simulate. The limitations of this validation process are (1) reliance on expert opinion and (2) lack of quantifiable data for the many variables included in the model. Serious model defects will usually expose themselves through some failure of the model to perform as would be expected of the actual system. If the model does not have any serious defects then the validated model becomes a management tool to conduct simulation experiments. In effect the model becomes a management laboratory (8:vii).

The reliability of the aircraft weapon system will be analyzed by entering two management concepts into the model. The first concept is the decision to improve training and technical data in order to improve personnel output. The second management concept to be considered is the reduction of maintenance levels from three levels to two levels. Further discussion of this analysis will be included in the final chapter.

Summary

In this chapter, the methodology of the research effort was presented. The system dynamics paradigm was discussed as well as a detailed explanation of the causal loop diagrams, flow diagrams, and DYNAMO equations. Through the use of these techniques, the reliability model will be

developed. In Chapter III, a step-by-step discussion of the relationships within each sector will be explained.

CHAPTER III

CAUSAL LOOP DESCRIPTIONS

Introduction

This chapter continues the conceptualization of the operational reliability model. The conceptual model development began in Chapters I and II at the highest level of abstract thinking, that is, at the apex of what Beer calls the "cones of resolution." These cones of resolution can be thought of as a thoroughness-abstraction hierarchy of models. At the top of the hierarchy is a very abstract model. At the bottom of the hierarchy is a very detailed and thorough model. Each succeeding level of resolution or model in the hierarchy contains additional details not found in the previous level (16:247-248). The operational reliability model development follows this hierarchical process. The causal loop diagrams in this chapter will provide more detail to the conceptual model already developed. The flow diagrams and equations in Chapter IV will further enrich the model and move it lower on the cone of resolution. The intent is to provide sufficient detail to make the model meaningful to policy makers at the Headquarters USAF level. Thus, the model will be looking at total aircraft operational reliability within USAF and not at a particular weapon system. All the variables used in

the model will be at this same level of resolution (for example, total aircraft inventory, total maintenance personnel, etc.).

The causal loop diagrams continue the conceptualization of the model by depicting the relationships among the variables in the three sectors of the model (Operations, Maintenance, and Research and Development). Causal loop diagrams provide a visual description to aid in the initial understanding of the system and are also of great value in discussing the system with the manager. Each sector will be explained through a step-by-step development of the pairwise relationships between variables within each sector. These pairwise relationships will be combined to form the complete causal loop diagram for the system.

Operations Sector

The Operations Sector is an essential part of the reliability system because it provides the ultimate test of the operational reliability of the system. For example, if a designated bomber does not hit its target, the system is not reliable. The causes of the failure might range from an inherent reliability problem of the equipment to the inexperience of the crew. In the Operations Sector, the model attempts to capture the idea of coordinating the essential variables into one unit so that the aircraft weapon system is able to perform its assigned mission.

Three important variables identified in this model are: (1) aircraft availability (AA), (2) crew availability (CA), and (3) flying hour availability (FHA). The weapon system cannot operate unless all three variables are accessible. These three variables determine the number of sorties scheduled (SS) as depicted in Figure 3-1.

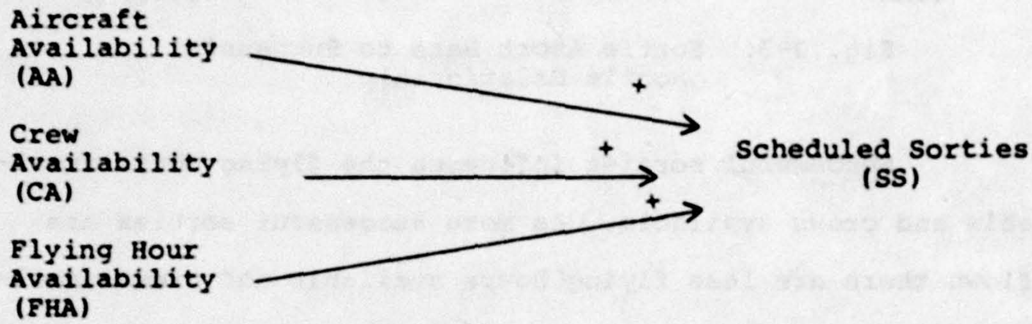

Fig. 3-1. Aircraft Availability, Crew Availability, and Flying Hours Availability to Scheduled Sortie Relationship

There is a positive relationship between the three variables and sorties scheduled because as the availability of these resources increases, scheduled sorties increase.

As the number of scheduled sorties increases, the number of potential successful sorties (SUCS) also increases giving the relationship a positive influence. This relationship is shown in Figure 3-2.

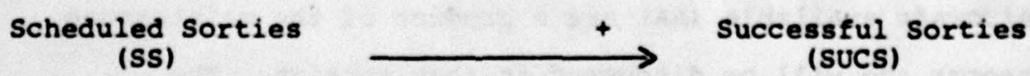

Fig. 3-2. Scheduled Sorties to Successful Sortie Relationship

Successful sorties are also influenced by the sortie abort rate (SAR). There is a negative relationship between these two variables. As the sortie abort rate increases, the number of successful sorties decreases. This relationship is shown in Figure 3-3.

$$\text{Sortie Abort Rate (SAR)} \xrightarrow{\quad - \quad} \text{Successful Sorties (SUCS)}$$

Fig. 3-3. Sortie Abort Rate to Successful Sortie Relationship

Successful sorties influence the flying hours available and crews available. As more successful sorties are flown there are less flying hours available and crews available, thus creating negative relationships between these variables. These pairwise relationships are depicted in Figure 3-4.

$$\text{Successful Sorties (SUCS)} \xrightarrow{-} \text{Crew Availability (CA)}$$

$$\text{Successful Sorties (SUCS)} \xrightarrow{-} \text{Flying Hour Availability (FHA)}$$

Fig. 3-4. Successful Sorties to Crew Availability and Flying Hour Availability Relationship

Successful sorties also influence the number of aircraft in maintenance (AM) because of the servicing involved and repairs made on other than mission essential equipment. Aircraft available (AA) are a product of the maintenance sector and will be discussed in that section. The

relationship between successful sorties and aircraft in maintenance is shown in Figure 3-5.

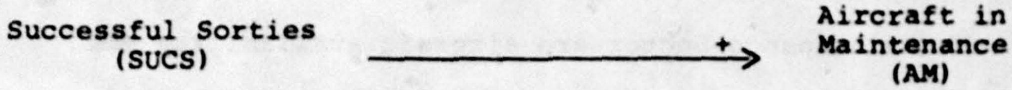

Fig. 3-5. Successful Sorties to Aircraft in Maintenance Relationship

A performance measure of the Operations Sector is the number of successful sorties. The management of the key variables of aircraft availability, crew availability, and flying hour availability determine the number of successful sorties that can be supported by the Operations Sector. The number of successful sorties can be compared with the measures in the other sectors, such as aircraft in maintenance and relative number of engineers to give an overall view of reliability. The Operations Sector is summarized in the causal loop diagram in Figure 3-6.

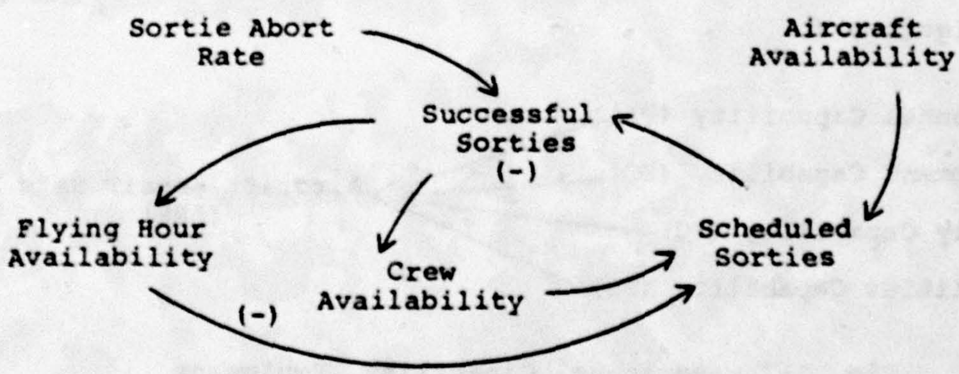

Fig. 3-6. Operations Sector Causal Loop Diagram

Maintenance Sector

In the Maintenance Sector, the restoration and servicing of aircraft is performed. The two key variables in the Maintenance Sector are aircraft availability and aircraft in maintenance. A production line is created between these two variables, because aircraft are either in available status or maintenance status. The aircraft repair rate (ARR) and the aircraft into maintenance rate (AIMR) determine what status the aircraft are in. There are also four factors that affect the repair rate. These factors are personnel capability, equipment capability, supply capability, and facilities capability. These four factors can be considered a consolidation of the Integrated Logistics Support System. The consolidation was made to simplify the model, while still retaining the essential features of the actual system being modeled. These factors determine the aircraft repair rate (ARR) and are illustrated in Figure 3-7.

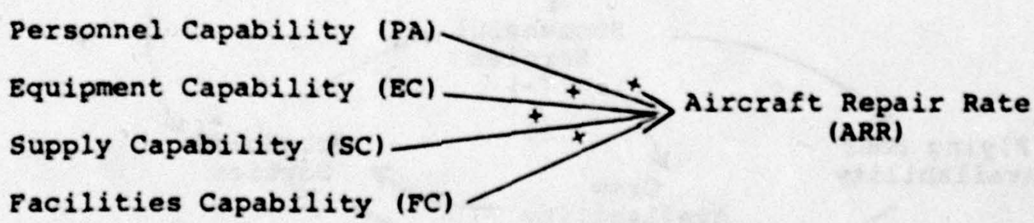

Fig. 3-7. Personnel Capability, Equipment Capability, Supply Capability, and Facilities Capability to Aircraft Repair Rate Relationship

There is a positive relationship between these factors and the aircraft repair rate, because as the capabilities increase, the aircraft repair rate also increases.

The aircraft repair rate has a negative relationship with aircraft in maintenance. As the aircraft repair rate increases, the number of aircraft in maintenance decreases. The causal diagram is in Figure 3-8.

Aircraft Repair Rate (ARR) $\xrightarrow{-}$ Aircraft in Maintenance (AM)

Fig. 3-8. Aircraft Repair Rate to Aircraft in Maintenance Relationship

As the aircraft in maintenance decrease, the aircraft available increase, making this a negative pairwise relationship. The causal diagram is in Figure 3-9.

Aircraft in Maintenance (AM) $\xrightarrow{-}$ Aircraft Availability (AA)

Fig. 3-9. Aircraft in Maintenance to Aircraft Availability Relationship

The number of aircraft in maintenance also has an influence on the capability factors mentioned above. As the number of aircraft in maintenance increase, the capability of the four factors decrease, creating negative relationships. This is because there is a finite capability existing in each element. As a portion of this finite capability is consumed, less capability exists to repair other aircraft. The practical effect of this relationship

is that there is a maximum repair rate and as the system approaches this maximum, there is little surge capability remaining. In other words, the system may be meeting all peacetime demands, but will have nothing in reserve to handle increased wartime requirements.

Personnel capability and equipment capability are also influenced by a maintainability factor which is a product from the Research and Development Sector. Maintainability will be discussed in the following section. The relationships between aircraft in maintenance, the capability factors, and maintainability are depicted in Figure 3-10.

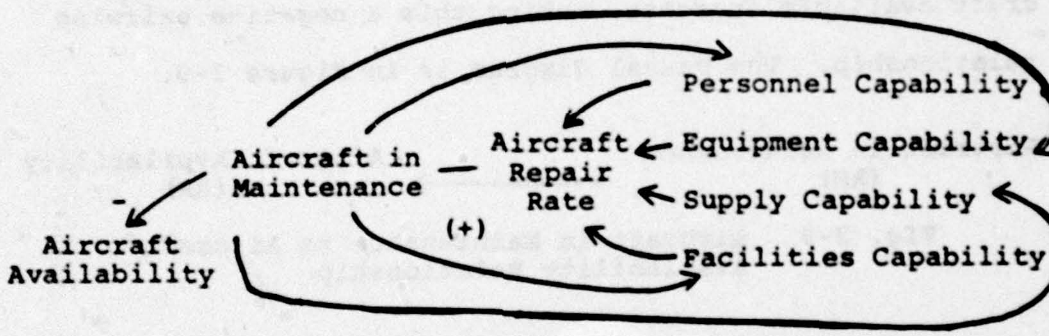

Fig. 3-10. Maintenance Sector Causal Loop Diagram

Figure 3-10 also summarizes the relationships within the Maintenance Sector. This sector depicts a positive causal loop indicating that there is a tendency for uncontrolled growth. For example, if the capabilities increase to such an extent that less and less aircraft are in maintenance, the capabilities will continue to grow.

The limiting variable in this sector, however, is the number of successful sorties. This variable will increase through the dynamic behavior of the model, thus increasing the number of aircraft in maintenance.

A key measure in this sector is the number of aircraft in maintenance because of the important effects this variable has on other elements in the sector and in the overall model. Also important is the aircraft repair rate which ultimately controls the number of aircraft in maintenance.

Research and Development Sector

The final sector to be developed in this chapter is the Research and Development Sector. The R&D Sector is an important sector because the output is engineering productivity. This productivity is in the form of inherent reliability and the maintainability built into a piece of equipment. Roberts stated in his book, The Dynamics of Research and Development, "The most critical production project resource is engineering manpower [14:19]." Capital investment is also included in the concept of the number of engineers produced. The basic assumption used in this sector is that if R&D acquires more engineers, composite spending will also occur in capital investment. Consequently, the more experienced engineers that are used productively, the more reliability and maintainability are produced.

Reliability and aircraft in maintenance influence the desired level of engineers (DLE). As reliability increases, the desired level of engineers decreases, but as aircraft in maintenance increase, the desired level of engineers also increases. These relationships are depicted in Figure 3-11.

Reliability $\xrightarrow{-}$ Desired Level of Engineers

Aircraft in Maintenance $\xrightarrow{+}$ Desired Level of Engineers

Fig. 3-11. Reliability and Aircraft in Maintenance to Desired Level of Engineers Relationship

As the desired level of engineers increases, the hiring rate of engineers (HR) increases, creating the positive relationship depicted in Figure 3-12.

Desired Level of Engineers (DLE) $\xrightarrow{+}$ Hiring Rate (HR)

Fig. 3-12. Desired Level of Engineers to Hiring Rate Relationship

As the hiring rate increases, new engineers also increase, thus providing another positive relationship. This relationship is depicted in Figure 3-13.

Hiring Rate (HR) $\xrightarrow{+}$ New Engineers (NE)

Fig. 3-13. Hiring Rate to New Engineers Relationship

There is a delay from the hiring of new engineers until they become productive, experienced engineers (EE). This relationship is positive and is shown in Figure 3-14.

$$\text{New Engineers (NE)} \xrightarrow{\quad + \quad} \text{Experienced Engineers (EE)}$$

Fig. 3-14. New Engineers to Experienced Engineers Relationship

Engineering manpower by itself is not a particularly useful concept. Currently, Air Force engineering manpower is in critical short supply. The Air Force is actively pursuing engineering graduates in order to increase this manpower level. In this model, engineering manpower will be converted into a technological base. It is the technology available and how much of this technology is incorporated into aircraft production that determines the actual improvements in maintainability and reliability.

The number of experienced engineers has a positive relationship with the technological base produced by the R&D Sector. The increase in the technological base increases both the inherent reliability and the maintainability of the aircraft equipment. These relationships are depicted in Figure 3-15.

$$\begin{tikzcd}
 & & \text{Reliability} \\
\text{Experienced Engineers (EE)} \arrow[r, "+"] & \text{Technology} \arrow[ur, "+"] \arrow[dr, "+"'] & \\
 & & \text{Maintainability}
\end{tikzcd}$$

Fig. 3-15. Experienced Engineers to Technology to Reliability and Maintainability Relationship

The Research and Development Sector is summarized in Figure 3-16.

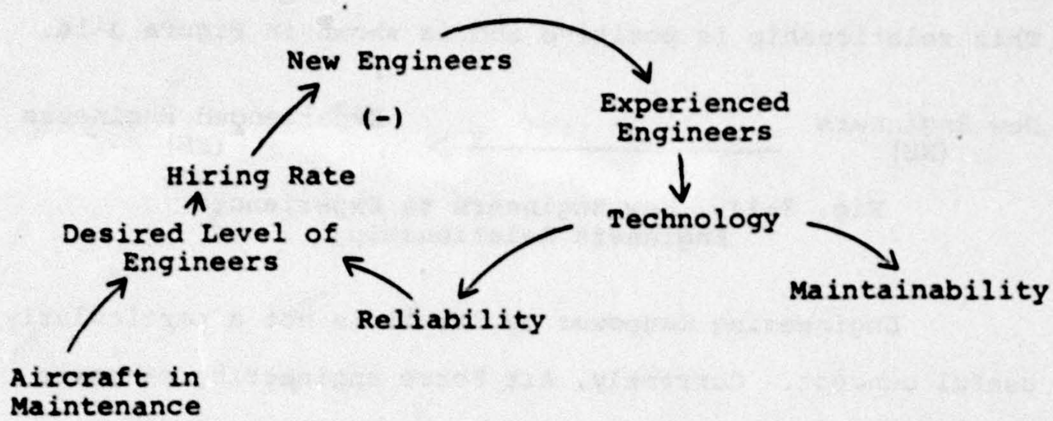

Fig. 3-16. Research and Development Sector Causal Loop Diagram

Composite Causal Loop Diagram

The entire model can now be illustrated through the combined pairwise relationships that have previously been described. This causal loop diagram will be the basis for the subsequent flow diagrams and equations that will be discussed in Chapter IV. This composite causal loop diagram is depicted in Figure 3-17.

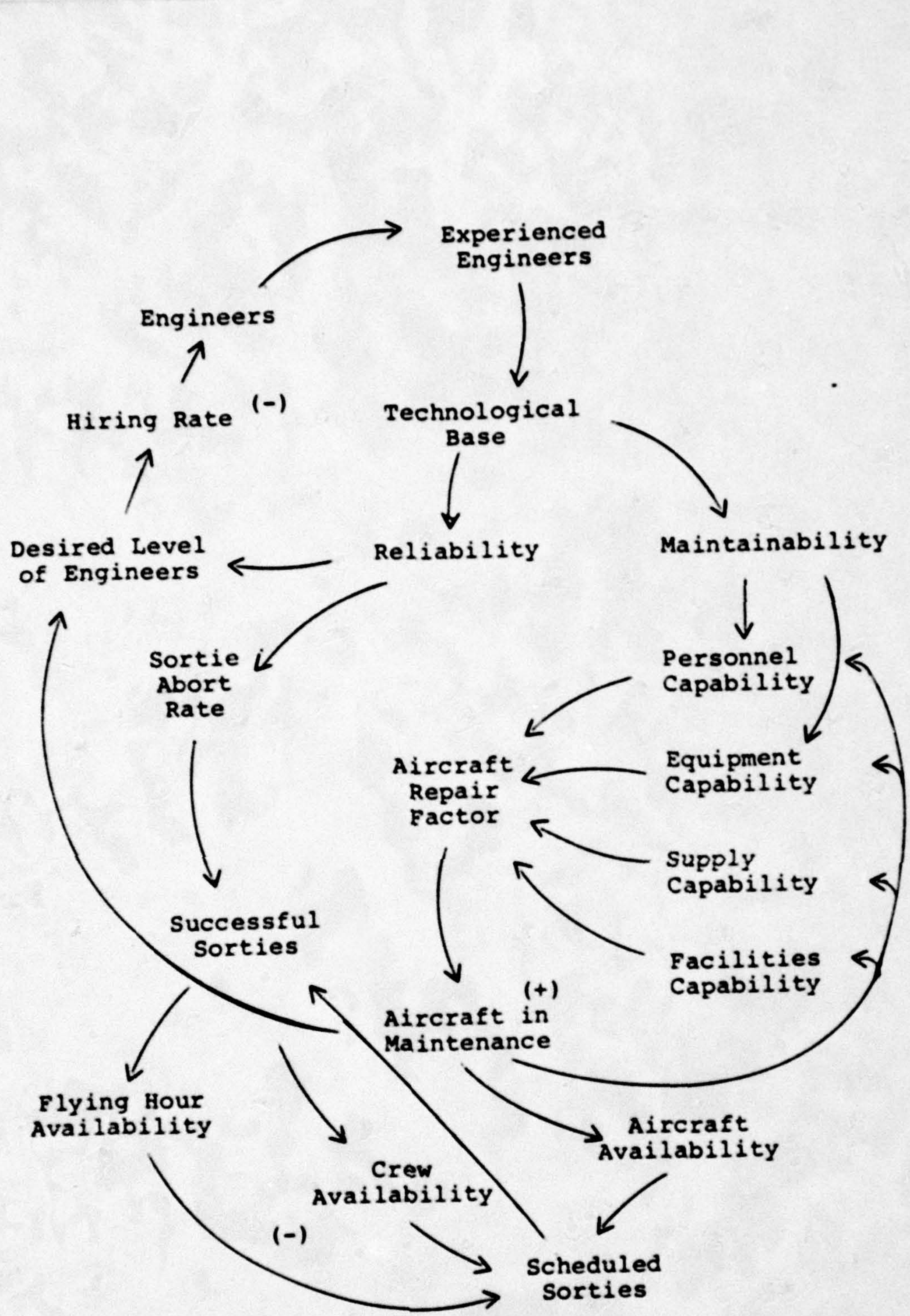

Fig. 3-17. Composite Causal Loop Diagram

CHAPTER IV

FLOW DIAGRAMS AND EQUATIONS

Introduction

Developed in Chapter III was the conceptual model of the operational reliability system through the verbal descriptions and causal loop diagrams. The task at hand in this chapter is to develop a structural model through flow diagrams. From these flow diagrams[1] DYNAMO equations will be constructed. These DYNAMO equations will be used to computerize the operational reliability model. A verbal description is included to provide the logic behind the development of the flow diagrams and DYNAMO equations. The structure of the model will be developed by sectors just as the causal loop diagrams were developed in Chapter III. The Maintenance Sector will be developed first. Figure 4-1 is the flow diagram for the Maintenance Sector.

Maintenance Sector

The Maintenance Sector has two levels, aircraft availability (AA)[2] and aircraft in maintenance (AM). This

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[1]The flow diagram symbology and an example is contained in Chapter II.

[2]The variable symbols used in the equations will be identified the first time the variable is used in this chapter.

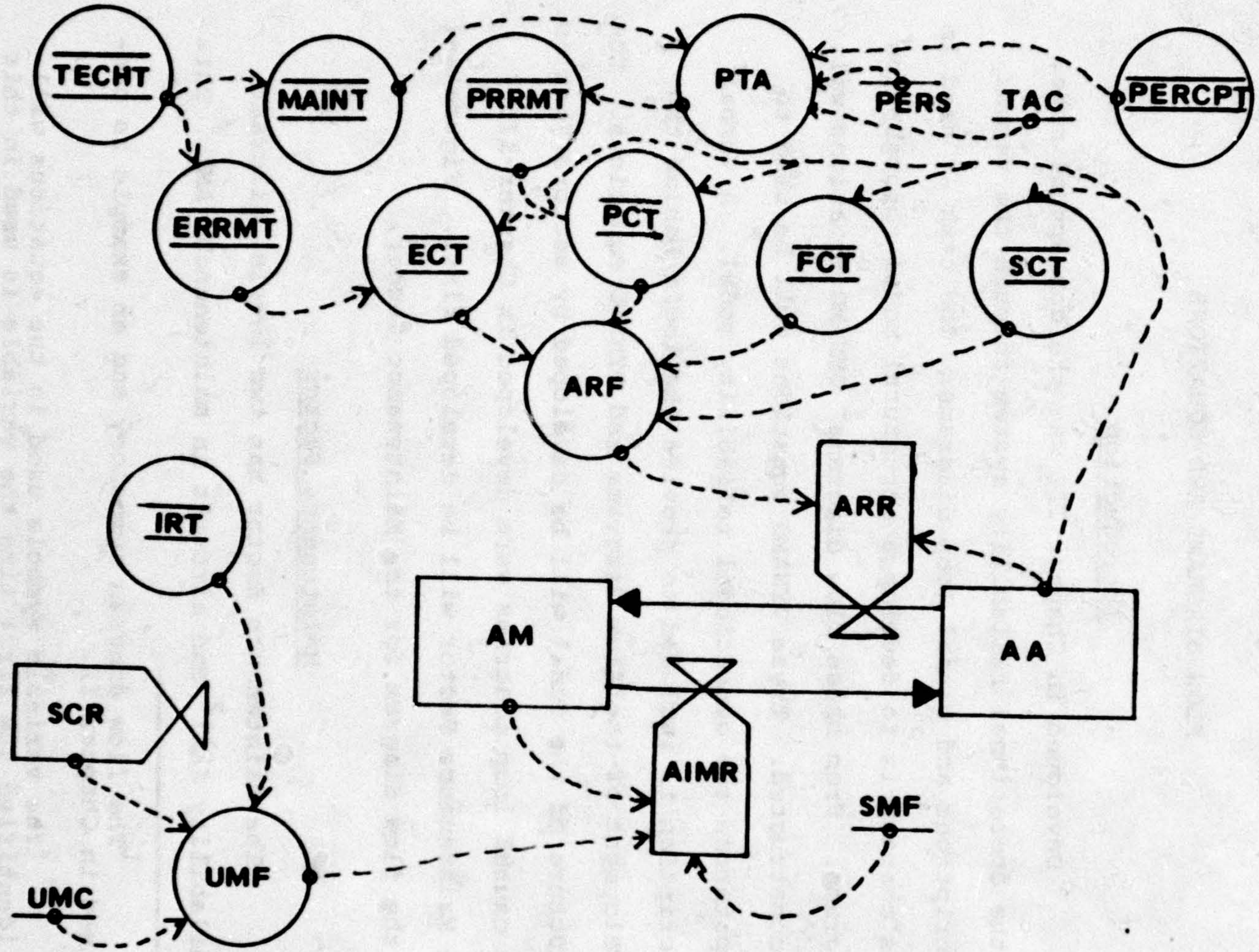

Fig. 4.1. Maintenance Sector

sector also has two rates, aircraft repair rate (ARR) and aircraft into maintenance rate (AIMR), which control the flows between the levels. The level equations are:

L AA.K=AA.J+DT*(ARR.JK-AIMR.JK)

L AM.K=AM.J+DT*(AIMR.JK-ARR.JK)

As can be seen from the level equations, the total number of aircraft available and aircraft in maintenance form a subsystem in which resources are conserved. That is, aircraft are neither added nor deleted. In this model, the total number of aircraft available and aircraft in maintenance is 8600. This is the approximate number of aircraft in the USAF inventory. Developed in the next section will be the rate equations.

The aircraft into maintenance rate is the total of all scheduled and unscheduled maintenance performed on the aircraft. Scheduled maintenance is a percentage of the level, aircraft available. The scheduled maintenance percentage includes Programmed Depot Maintenance (PDM). Unscheduled maintenance is a percentage of the sortie completion rate (SCR). The sortie completion rate will be developed later in the chapter. Unscheduled maintenance is the maintenance tasks that are required as a result of flying aircraft. Therefore, the more sorties that are flown, the more unscheduled maintenance will be required. The aircraft into maintenance rate equation is:

R AIMR.KL=SMF.K*AA.K+UMF.K*SCR.JK

where SMF is the scheduled maintenance factor and UMF is the unscheduled maintenance factor. It must be noted that if aircraft available drops to a low number, then the number of aircraft going into scheduled maintenance will also be a low number. This is a valid situation for two reasons. First, because many of the scheduled maintenance tasks are of a routine nature, the maintenance tasks can be postponed temporarily until more aircraft are available for scheduling. This situation occurs frequently at base level when operational requirements are high. Secondly, if the aircraft are not available for scheduled maintenance it must be because the aircraft are flying sorties. The increase in flying sorties increases the unscheduled maintenance performed. Consequently, many of the scheduled maintenance tasks will be performed concurrent with the unscheduled maintenance tasks.

The unscheduled maintenance factor includes an unscheduled maintenance constant (UMC) and inherent reliability (IR). Inherent reliability is included because as more reliability is designed into the equipment one would expect to have fewer failures and consequently, less maintenance to perform. The equations are:

A UMF.K=UMC-IR.K

C UMC=.3

The formulation of the aircraft repair rate equation was considerably more complex than was the formulation of the aircraft into maintenance rate equation. Recall from Chapter III that four factors made up the aircraft repair rate. The factors are personnel capability (PC), supply capability (SC), equipment capability (EC), and facilities capability (FC). The total capability provided by these four factors is the aircraft repair factor (ARF). The aircraft repair rate is the aircraft repair factor multiplied by the number of aircraft in maintenance. Because performing maintenance requires a certain amount of time, a DYNAMO third order delay function, DELAY3, is used to simulate the actual repair rate. The equations just described are:

```
R    ARR.KL=DELAY3(AR.K,MDEL)
C    MDEL=Average days aircraft remain in maintenance
A    AR.K=ARF.K*AM.K
A    ARF.K=(PC.K+SC.K+EC.K+FC.K)/100
```

The values for personnel capability, supply capability, equipment capability, and facilities capability are all derived from DYNAMO table functions. Table functions were used in this model because adequate Air Force measures for these capabilities do not exist. The table functions provide the modeler with the capability to estimate what the relationship between two variables might be.

Figures 4-2, 4-3, 4-4, and 4-5 contain the graphical representations of the relationships between the four capability factors and aircraft in maintenance. These relationships are in terms of relative numbers only. That is, the numbers have no meaning outside this model. Possible ways to measure these numbers in the actual operational environment will be discussed in Chapter V. The authors recognize that the use of the table functions in DYNAMO without empirical evidence to substantiate the relationships can create questions about the external validity of this model (2:391). To preclude a portion of this criticism, sensitivity analysis using different numerical relationships within the table functions will be conducted. The results of this validity check are discussed in Chapter V.

The concept embedded in each of the four capability factors is that a finite capability exists. This limited capability can only repair a maximum number of aircraft. As more aircraft are in need of maintenance, less capability remains to repair additional aircraft. This means that the aircraft repair rate will increase as aircraft in maintenance increase until all the capability is consumed. If more aircraft require maintenance, a queue of aircraft awaiting maintenance will develop. In this situation, there is no capability to draw upon in the event of increased demands. Thus, how much capability is remaining could be very important in determining the amount of increased

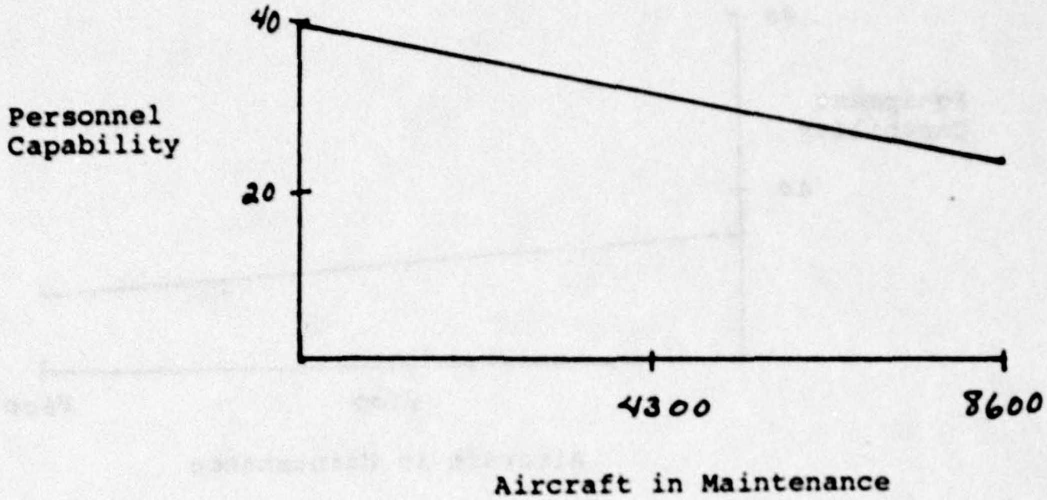

Fig. 4-2. Personnel Capability

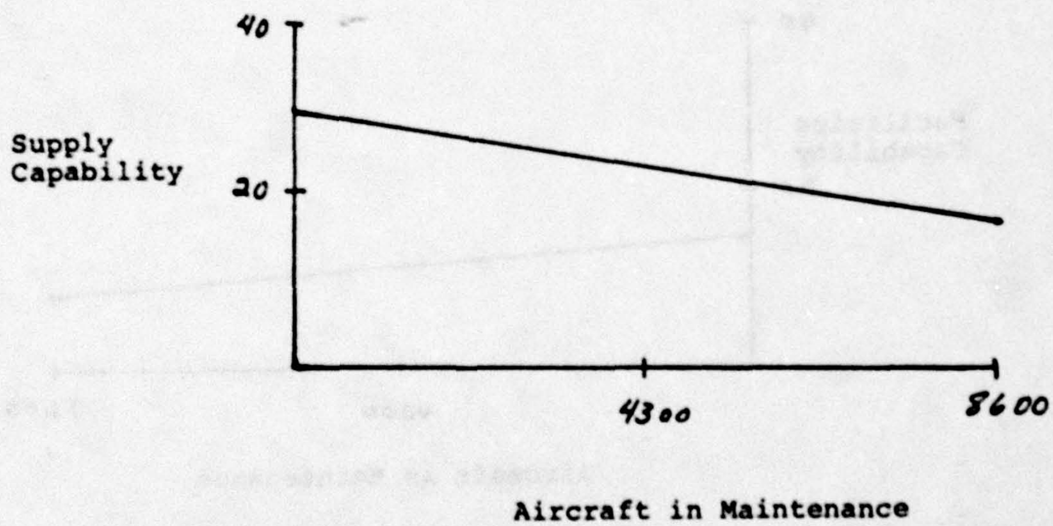

Fig. 4-3. Supply Capability

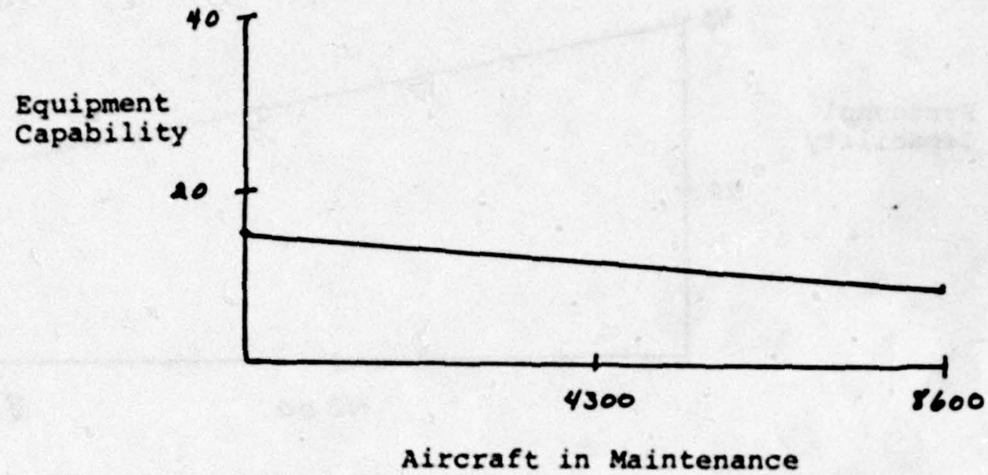

Fig. 4-4. Equipment Capability

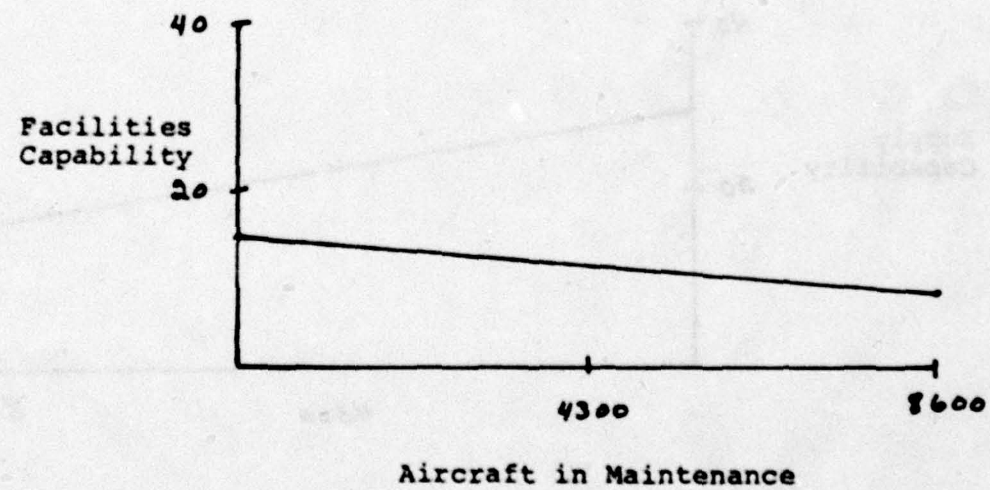

Fig. 4-5. Facilities Capability

flying that can be accomplished. For example, a wing or squadron may be meeting its peacetime flying commitments, but may require 90 percent to 100 percent of its maintenance capability to accomplish it.

Two of the capability factors, personnel and equipment, have additional variables that influence the values obtained from the tables. Personnel capability is influenced by the personnel repair rate multiplier (PRRM). This multiplier is obtained from another table function. This multiplier is based on the fact that improvements in technology will result in improvements in maintainability. These improvements in maintainability allow a maintenance technician to perform more maintenance tasks than could previously have been accomplished. This means that the personnel capability has been increased. The equations and table functions for personnel capability are:

```
A   PC.K=TABHL(PCT,AM.K,0,8600,1075)*PRRM.K

T   PCT=40/38/36/34/32/30/28/25/23

A   PRRM.K=TABHL(PRRMT,PPA.K0,.5,.1)

T   PRRMT=.8/.88/.96/1.04/1.12/1.2

A   PPA.K=(PERCP.K/MAIN.K)*(PERS/TAC)

A   PERCP.K=TABHL(PERCPT,MAIN.K,0.1,.2)

T   PERCPT=0/.001/.004/.009/.016/.025

A   MAIN.K=TABHL(MAINT,TECH.K,0,1,.1)

T   MAINT=.001/.02/.03/.04/.06/.08/.1/.15/.2/.4/1
```

C PERS=Total number maintenance personnel in USAF

C TAC=Total number aircraft in USAF inventory

Figures 4-6, 4-7, and 4-8 contain the graphs of the table functions for personnel repair rate multiplier, personnel capacity (PERCP) and maintainability (MAIN), respectively.

Equipment capability is also enhanced through technological improvements. This enhancement is accomplished in the model through the equipment repair rate multiplier (ERRM). The value of the equipment repair rate multiplier is determined through a table function by the value of technology. Figure 4-9 shows this relationship in graphical form.

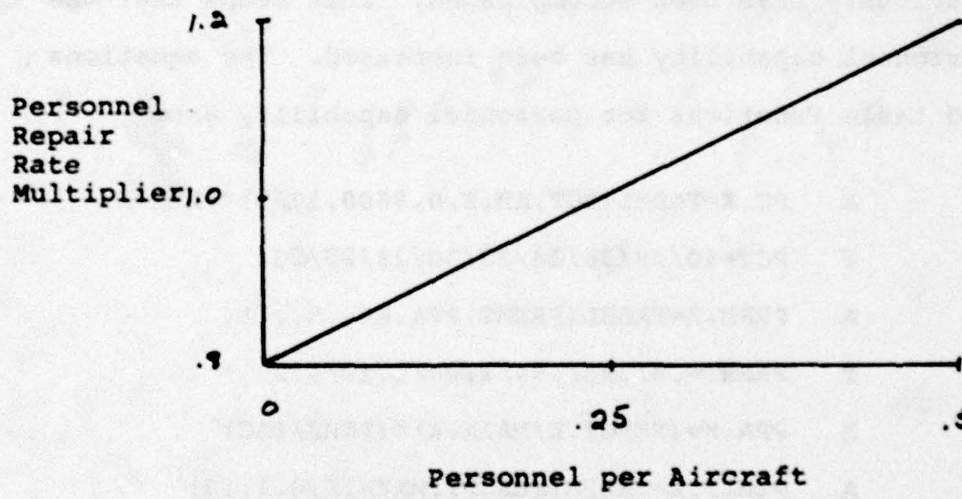

Fig. 4-6. Personnel Repair Rate Multiplier

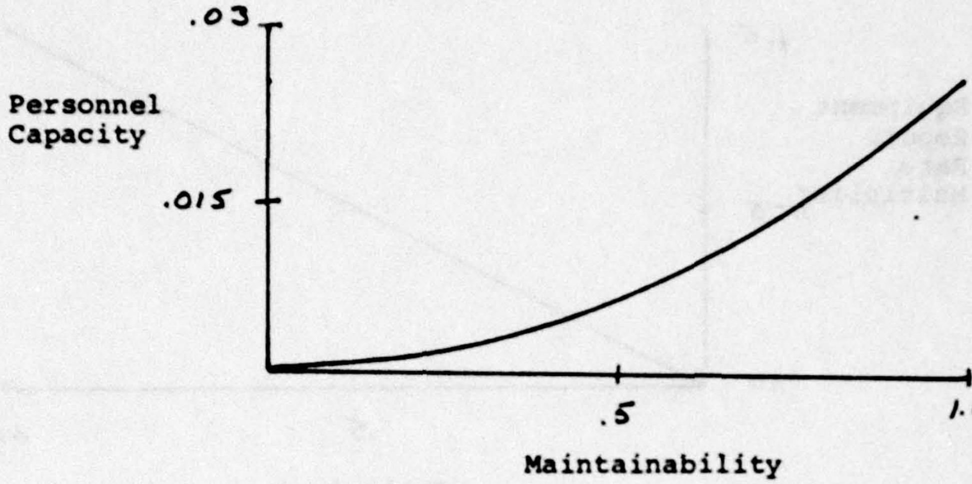

Fig. 4-7. Personnel Capacity

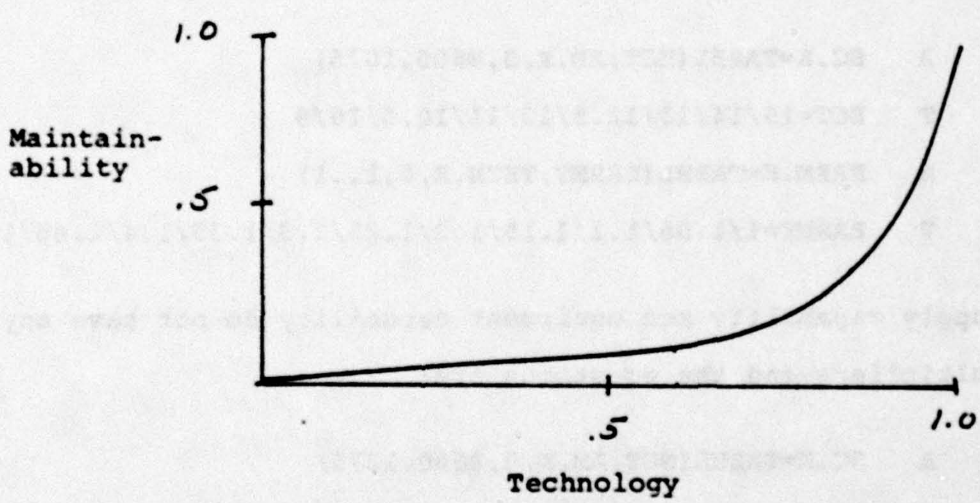

Fig. 4-8. Maintainability

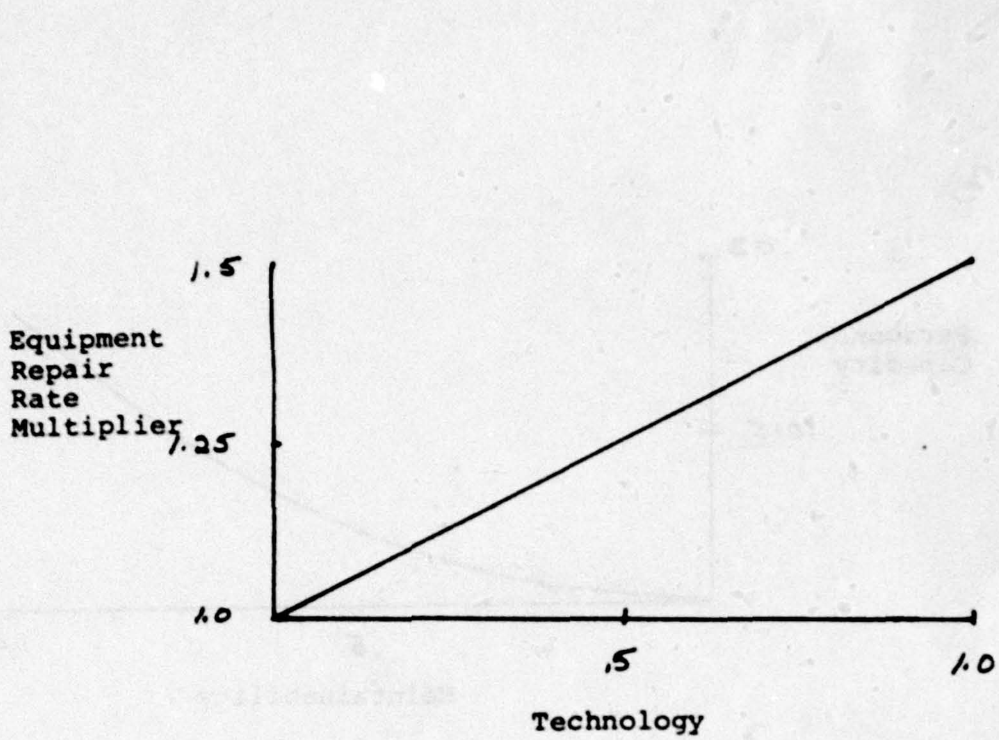

Fig. 4-9. Equipment Repair Rate Multiplier

The equations for equipment capability are:

A EC.K=TABHL(ECT,AM.K,0,8600,1075)

T ECT=15/14/13/12.5/12/11/10.5/10/9

A ERRM.K=TABHL(ERRMT,TECH.K,0,1,.1)

T ERRMT=1/1.05/1.1/1.15/1.2/1.25/1.3/1.35/1.4/1.45/1.5

Supply capability and equipment capability do not have any multipliers and the equations are:

A SC.K=TABHL(SCT,AM.K,0,8600,1075)

T SCT=30/28/27/25/24/22/20/19/17

A FC.K=TABHL(FCT,AM.K,0,8600,1075)

T FCT=15/14/13/12.5/12/11/10.5/10/9

This completes the development of the Maintenance Sector. The Operations Sector will be developed next.

Operations Sector

The Operations Sector of this model determines how many aircraft sorties will be scheduled and ultimately flown. There are three potentially limiting factors: (1) the number of flying hours available, (2) the number of crews available, and (3) the number of available aircraft. Figure 4-10 contains the flow diagram depicting the relationships among these variables.

An assumption used in the model is that each sortie scheduled requires one crew, and there was no delay involved in turning crews around to make them available to fly more sorties. This assumption is reasonable in that it is unlikely that all crews will be used at the same time. If this condition were to occur, then those crews would require crew rest before becoming available to fly more sorties. The delay caused by the crew rest period, however, is sufficiently short to become lost in the noise level of the system.

The first equation developed in this sector incorporates flying hours available (FHA) into the model. The equation is:

```
L    FHA.J=FHU.J+PULSE(PH,364,364)+PULSE(PH1,273,364)
```

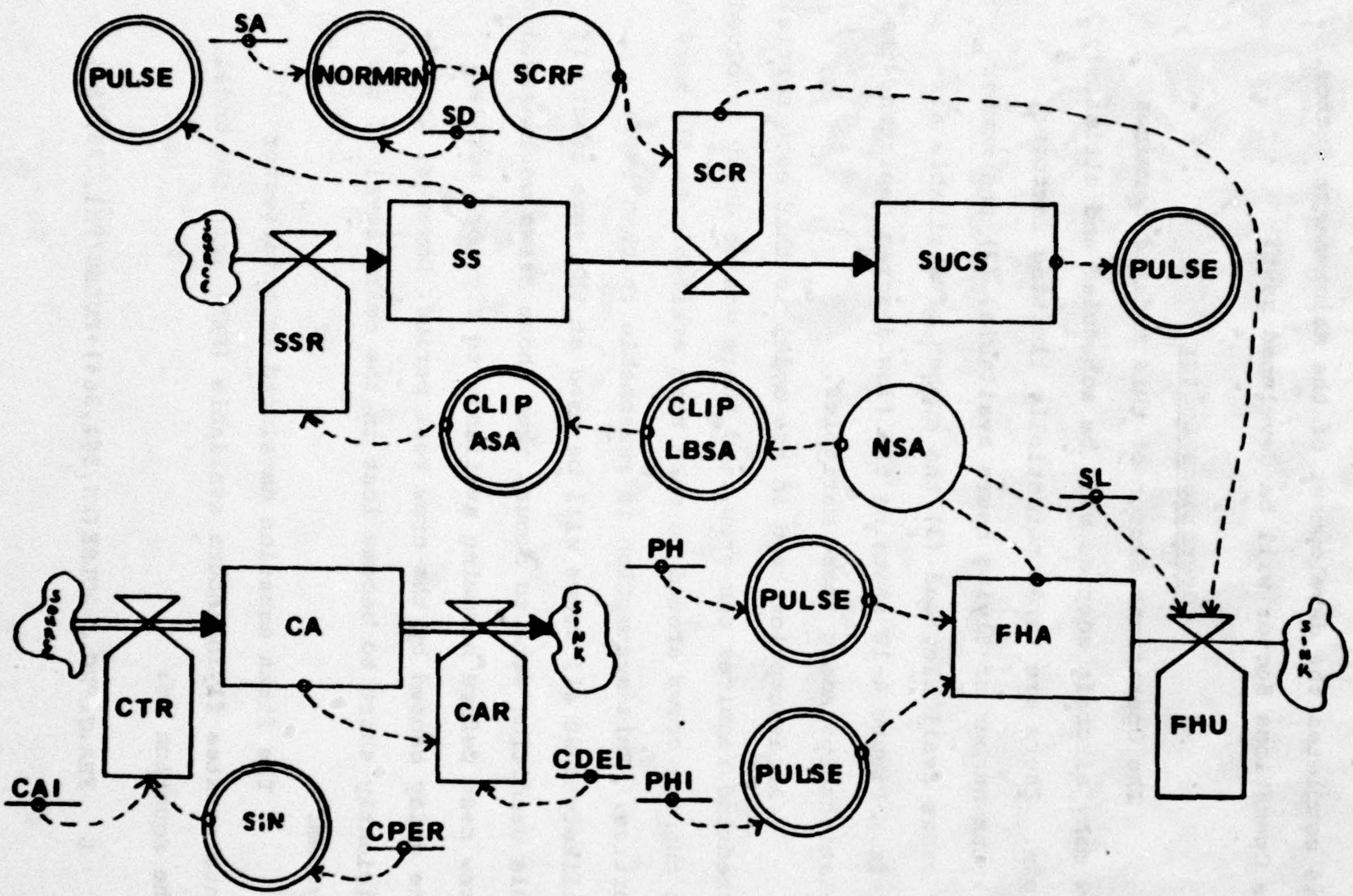

Fig. 4-10. Operations Sector

The pulse functions input flying hours yearly with every fourth quarter having an input higher than the other three quarters. This allocation of flying hours is consistent with how the Air Force allocates flying hours to the operating commands. The fourth quarter allocation is larger because there has been a historical trend to fly more in the summer (13:144). FHU is flying hours used and represents the flying hours consumed by the aircraft sorties flown. The equation for flying hours used is:

A   FHU.K=SCR.JK*SL

where SCR is the sortie completion rate and SL is the average sortie length. A sortie length of 3.5 hours was used in this model. This is the average sortie length of bomber, cargo, and fighter aircraft.

The number of crews available (CA) is the second variable which could potentially limit the number of sorties that might be flown. The equation for crews available is:

L   CA.K=CA.J+DT*(CTR.JK-CAR.JK)

where CTR is the crew training rate (not crew proficiency training) and CAR is the crew attrition rate. The level of crews available to fly sorties is determined by the difference between the number of trained crews and the number of crews no longer available because of retirement or reassignment.

The crew training rate depends on the number of crews available initially (CAI) and a sinusoidal input function. Crews available initially was determined by using an average crew ratio of 2.0 multiplied by the approximate number of aircraft in the inventory (8600) (13:144). The sinusoid input simulates a ten-year cycle between the high and low points of crew availability. The Air Force appears to go through a period of too many pilots and navigators which induces top level management to make cutbacks in the training of new crews. Approximately five years later there are too few pilots and navigators, and the policy decision is made to train more crews. The crew training rate equation is:

R   CTR.KL=(CAI+(1.0*SIN(6.283*TIME.K/CPER)))/DT

The crew attrition rate is determined by the average time a crew, once trained, remains on flying status. The crew attrition rate equation is:

R   CAR.KL=CA.K/CDEL

C   CDEL=Average time on flying status

The third potential factor which could limit the number of sorties flown was aircraft availability. The equation for aircraft availability was developed in the Maintenance Sector.

Having explained the factors which determine the number of sorties that can be flown, the equation for scheduled sorties (SS) can be constructed. The equation is:

L SS.K=SS.J+DT*(SSR.JK)+PULSE(-SS.J,364,364)

This equation collects scheduled sorties for each year. Scheduled sorties increase by the scheduled sortie rate (SSR). The pulse function empties the level yearly. The depletion of the level is done to keep scheduled sorties from growing to an unrealistic number.

A set of decision rules was developed to determine the scheduled sortie rate. The initial step was to determine a daily rate of flying sorties that would use up the flying hours available. This was accomplished by use of the following equation.

A NSA.K=((FHA.K/SL)/(365-YTIM.K))*DT

where NSA is the number of sorties available and YTIM is a timing function to count the number of days in a year. A DYNAMO clip function was used to select the smaller of the two numbers, sorties available or aircraft available. The smaller number becomes the limit between sorties/aircraft (LBSA). The equation is:

A LBSA.K=CLIP(NSA.K,AA.K,AA.K,NSA.K)

The value stored in limit between sorties/aircraft is compared with crews available, and the smaller number is stored in available scheduled aircraft (ASA). The equation is:

A ASA.K=CLIP(LBSA.K,CA.K,CA.K,LBSA.K)

Available scheduled aircraft becomes the scheduled sortie rate in the equation:

R SSR.K.=ASA.K

After scheduling the sorties, the number of successful sorties (SUCS) can be determined. The equation for successful sorties is:

L SUCS.K=SUCS.J+DT*(SCR.JK)+PULSE(-SUCS.J,364,364)

The sortie completion rate (SCR) determines the level of successful sorties. The pulse function is used in the same manner as it was in the level equation for scheduled sorties. The sortie completion rate is a function of the scheduled sortie rate and a sortie completion rate factor (SCRF). The sortie completion rate factor is a function of sortie aborts (SA) and an inherent reliability multiplier (IRM). The sortie abort rate is a percentage obtained from KO 51 System Effectiveness Reports. Sortie aborts is input to a random number generator which provides the normal random deviates used in the model. The inherent

reliability multiplier recognizes that as more inherent reliability is designed into the aircraft, the number of sortie aborts will decrease. The set of equations just described is:

```
R    SCR.KL=SSR.JK*SCRF.K
A    SCRF.K=1-NORMRN(SA,SD)*IRM.K
C    SA=.04
C    SD=.02
A    IRM.K=1-IR.K
```

This completes the equation set for the Operations Sector. The third and final sector of this model, Research and Development, will be covered next.

Research and Development Sector

Discussion of the Research and Development Sector will complete the presentation of the Operational Reliability Model. The flow diagram for this sector is contained in Figure 4-11. The first level equation in this sector provides the number of new engineers (E). The equation for this level is:

```
L    NE.K=NE.J+DT*(HR.JK-EER.JK)
```

The number of new engineers is controlled by the hiring rate (HR) and the experienced engineer rate (EER).

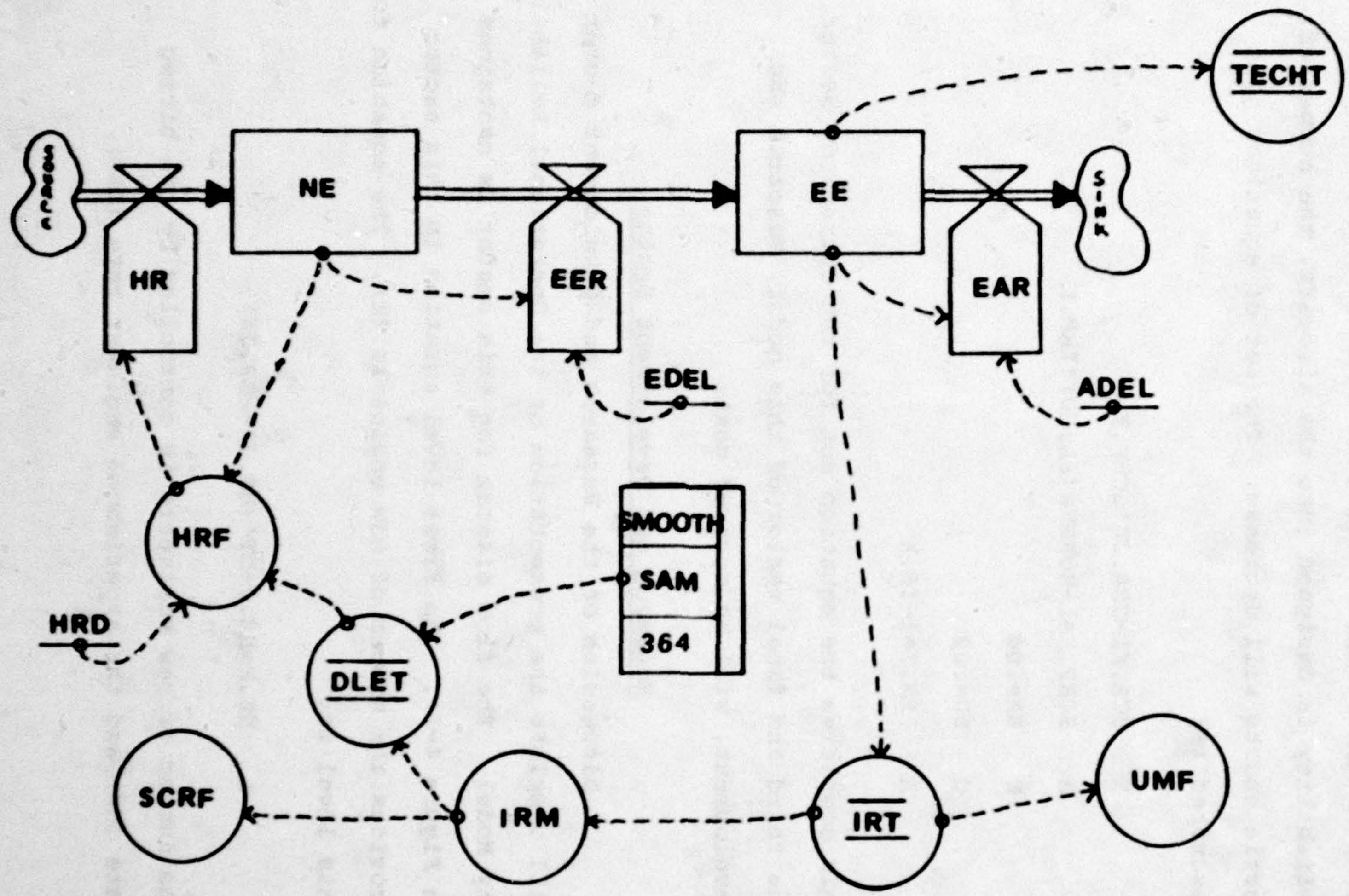

Fig. 4-11. Research and Development Sector

The hiring rate is determined by the hiring rate factor (HRF). The hiring rate factor is the difference between a desired level of engineers (DLE) and the level of new engineers divided by a hiring rate delay (HRD). This delay represents the amount of time it takes to begin hiring new engineers after the policy decision has been made to hire. The experienced engineer rate is the level of new engineers divided by the time required for new engineers to gain experience. The equation set is:

```
R    HR.KL=HRF.K
A    HRF.K=(DLE.K-NE.K)/HRD
C    HRD=728
R    EER.KL=NE.K/EDEL
C    EDEL=728
```

The desired level of engineers is determined by a table function using the number of aircraft in maintenance as the independent variable. Figure 4-12 provides a graph of the relationship between the desired level of engineers and the number of aircraft in maintenance. The value obtained from the table is modified by the inherent reliability multiplier. This is because as inherent reliability in equipment increases, the desire for more engineers decreases.

As explained in Chapter III, the need for engineers increases as the number of aircraft in maintenance increase.

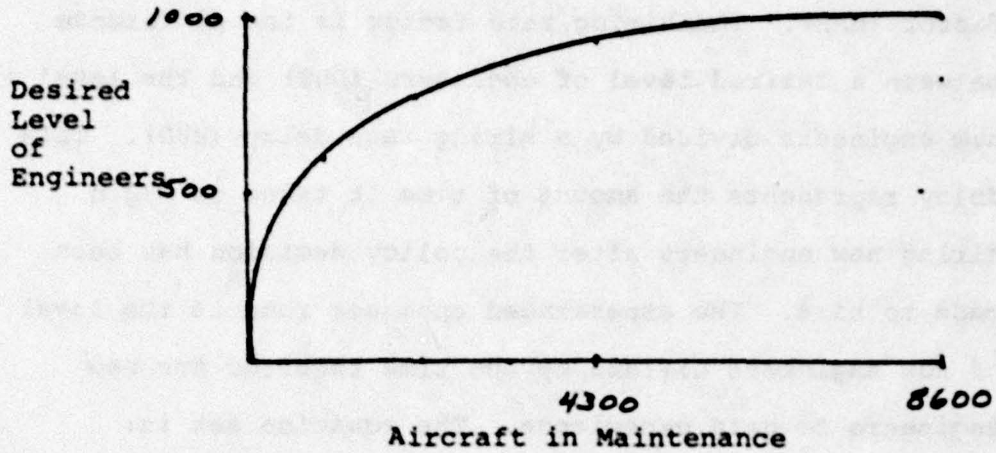

Fig. 4-12. Desired Level of Engineers

A DYNAMO smooth function is used as the input argument to the table function. The smooth function filters out any short-term fluctuations in aircraft in maintenance. The equations just described are:

```
A    SAM.K=SMOOTH(AM.K,364)
A    DLE.K=TABHL(DLET,SAM.K,0,8600,1075)*IRM.K
T    DLET=0/650/760/830/950/1000/1000/1000
```

As explained previously, the new engineers become experienced engineers (EE) through training and knowledge gained from the job. At the same time, experienced engineers retire or leave to take other jobs. The experienced engineering rate has already been developed. The

engineering attrition rate (EAR) is the level of experienced engineers divided by the average time an engineer remains working. The equations are:

```
L   EE.K=EE.J+DT*(EER.JK-EAR.JK)
R   EAR.KL=EE.K/ADEL
C   ADEL=3640
```

The two outputs from the Research and Development Sector are inherent reliability (IR) and technology (TECH). Both of these variables have values determined by table functions which use experienced engineers as the input argument. Figures 4-13 and 4-14 contain graphs of the relationships.

The equations for inherent reliability and technology are:

```
A   IR.K=TABHL(IRT,TECH.K,0,1.0,.25)
T   IRT=.01/.015/.04/.1/.2
A   TECH.K=TABHL(TECHT,EE.K,0,1000,100)
T   TECHT=0/.07/.2/.35/.45/.5/.55/.65/.8/.93/1
```

The table functions in this sector depict relative relationships only. As was stated earlier, these variables described by table functions point out the need for quantitative measurement to determine their actual importance in influencing system behavior.

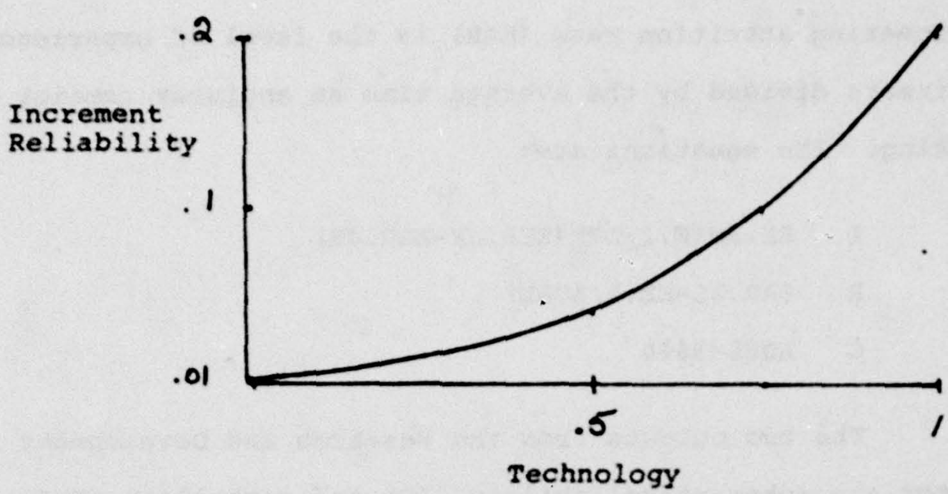

Fig. 4-13. Inherent Reliability

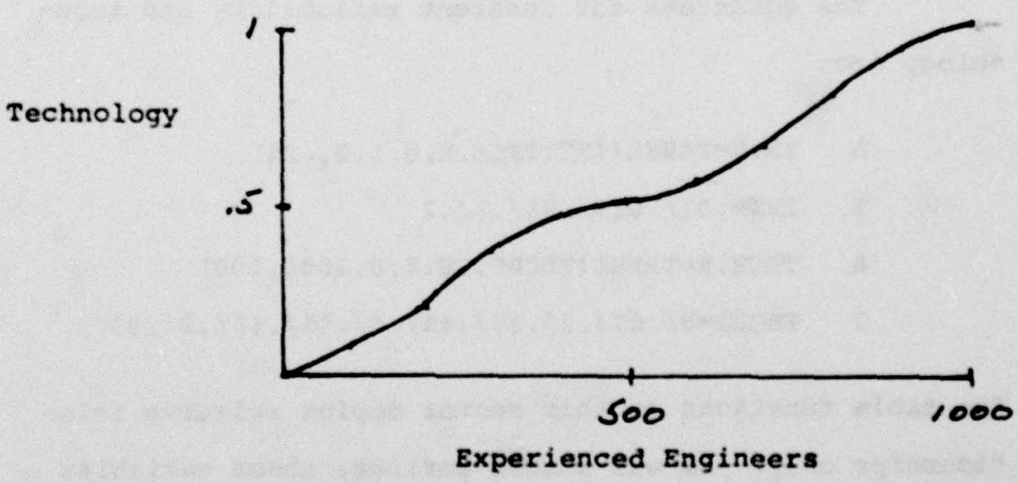

Fig. 4-14. Technology

This completes the development of the equation set for the Research and Development Sector. It also signals the completion of the structural model and the equations necessary to computerize the model. A flow diagram of the entire model is in Figure 4-15. A listing of all the equations in the basic model can be found in Appendix A.

Chapter V will describe the basic runs made with the model. Sensitivity analysis will be conducted to determine variables that are important to model behavior. Chapter V will end with conclusions and recommendations that are generated by conducting the simulation experiments.

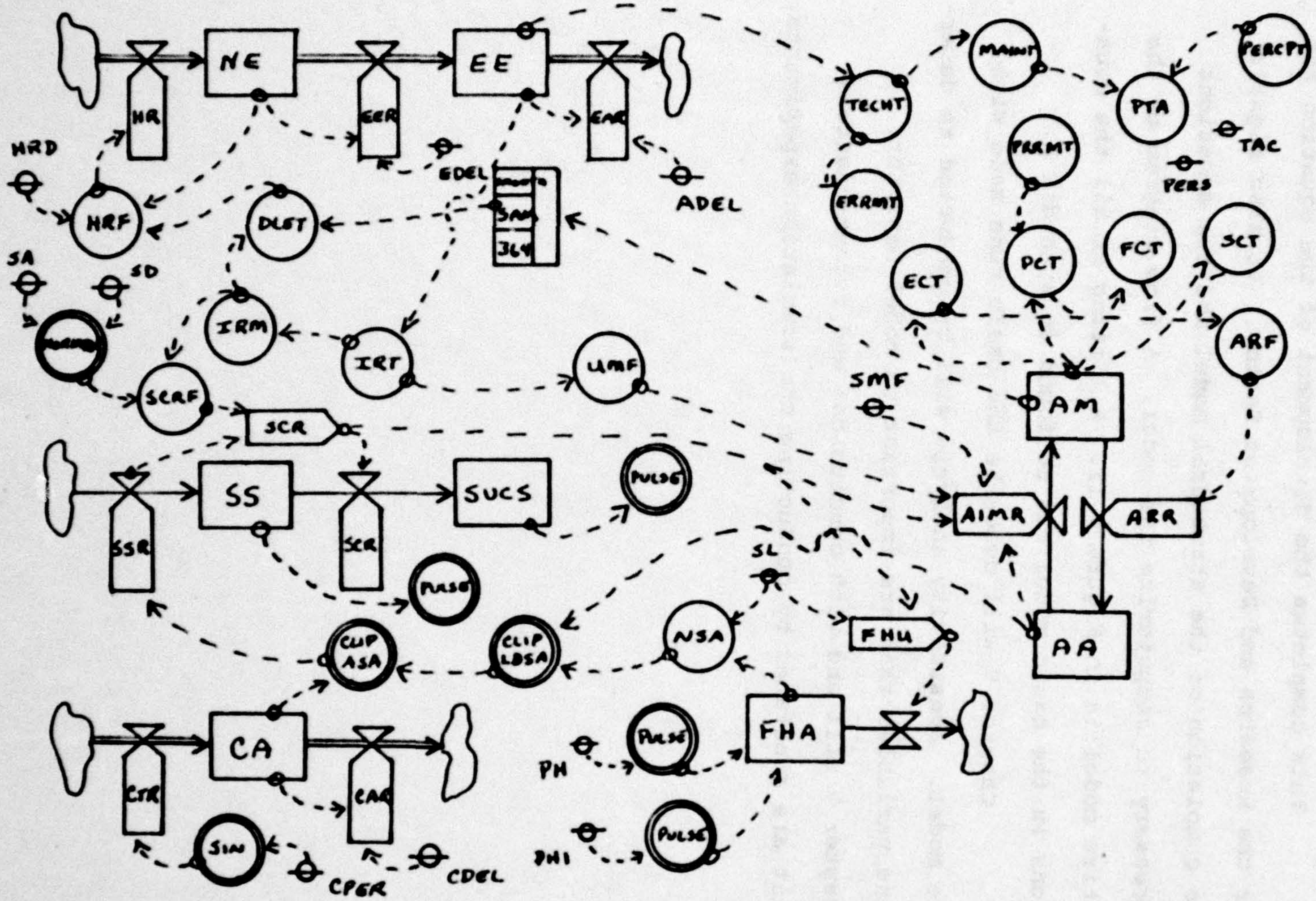

Fig. 4-15. System Flow Diagram

CHAPTER V

MODEL VALIDATION, SENSITIVITY ANALYSIS, AND CONCLUSIONS

Introduction

Discussed in Chapter V will be the validation and sensitivity analysis of the Operational Reliability Model. Conclusions and recommendations for continuing research will complete the chapter.

The Operational Reliability Model, developed through the system dynamics paradigm, is a representation of the complex reliability system. The model was used to evaluate current policy as well as policy changes that may improve the reliability system. The model demonstrated the potential effects that these policy changes may have on the operational reliability of aircraft weapon systems.

Initial Simulation Run

The initial simulation run was used for two purposes. First, an initial run was made to ascertain if the model reproduced actual system behavior. The results are covered in more detail in the section on model validation. Secondly, the results from the first simulation run were used as the basis for comparison with the other simulation runs which incorporate policy changes. The plot of this first run is contained in Appendix C.

The time period for the initial simulation run and each subsequent run was five years. The five-year period was chosen as the time in which policy changes make their effects apparent in system behavior. Six variables were chosen as measures of system performance. The variables are aircraft availability, aircraft in maintenance, aircraft repair rate, sortie completion rate, repair capability, and aircraft maintenance capability.

The research indicated that the sortie completion rate was the best, single measure of operational reliability. As shown in the results, the sortie completion rate was fairly constant relative to the flying hours available. The number of aircraft in maintenance also provides valuable information about the operational reliability of the system. Too many aircraft in maintenance indicated that there were too few aircraft available to fly sorties. This fact would cause the sortie completion rate to decrease. The aircraft repair rate was the key factor in determining the throughput of aircraft in maintenance. The aircraft repair rate must be sufficient to make aircraft available to fly sorties. The aircraft repair rate is dependent on the maintenance capability of the Air Force. This maintenance capability is in large part a determinant of the total capability of the Air Force to perform assigned missions. It appears then, that a finding of this research supports

the conclusion that operational reliability is a function of the total Air Force capability.

Operational Reliability = f(Total Air Force Capability)

Thus, a critical problem identified by this research was to measure the total Air Force capability. An attempt to determine a measure of this capability was considered next.

Repair capability and aircraft maintenance capability were computed by supplementary equations only to provide output measures. Appendix B contains the formulation of these two equations. Repair capability and aircraft maintenance capability measure the capability remaining to repair additional aircraft as well as those already in repair. Repair capability was in the units, percentage of aircraft per day. Aircraft maintenance capability was measured in units of aircraft per day.

These measures are consistent with the definitions of personnel, supply, equipment, and facilities capabilities. These definitions stated that there was only a finite limit to the total maintenance capability. Each aircraft in maintenance consumed a portion of the total capability was measured by repair capability and aircraft maintenance capability.

Measurements such as repair capability and aircraft maintenance capability appear to be important to determine surge capability to meet unforeseen contingency actions.

Currently used measures of system performance such as Not Mission Capable Supply (NMCS),[1] measure only the areas which are experiencing difficulties. On an Air Force-wide basis, measurement of the total capability available has been difficult to determine. Military exercises are conducted periodically in an attempt to exercise and determine what this capability may be. These exercises are costly, of short duration, and normally well planned. Therefore, they may not be indicative of a long-term, substantial level of operations. A suggestion on how to measure this capability is provided in the conclusions section.

The output from each simulation run was contained in two plots. One plot contained the output for the flying hours available, aircraft available, aircraft in maintenance, and aircraft repair rate. The other plot contained the output for sortie completion rate, repair capability, and aircraft maintenance capability. Each plot provided a time scale in days along the vertical axis with one block representing one year. The horizontal axis provided the scale for each variable. A legend was included with each plot matching the variable symbol with the symbol used on the plot.

---

[1]NMCS is a new term which is the rough equivalent of the older more familiar term Not Operationally Ready Supply (NORS).

The plots from the initial simulation run showed the model variables in equilibrium for the first three years. Flying hours available were being consumed on a yearly basis, and the sortie completion rate was relatively constant. The increase in the sortie completion rate near the end of each year corresponded to the increase in allocated flying hours for the fourth quarter of each year. At the three-year point, increased technology from the Research and Development Sector began to exert an effect on model behavior. The variable changes were all within a 3-7 percent range except for the aircraft maintenance capability which changed approximately 20 percent. The next section discusses how well these results compare with actual system behavior.

Model Verification/Validation

Model verification consisted of determining that the model equations did, in fact, correspond to the system structure that was developed by the flow diagrams in Chapter IV. Because the equations were developed concurrent with the flow diagrams, verification of the model has already been accomplished.

Validation of the model was determined by comparing the results from the initial run with the actual behavior of the system under study. The initial simulation results indicated a stable system with a constant sortie completion

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rate (peaking in the summer) and constant values for aircraft availability and aircraft in maintenance. These results could not be compared directly with the actual operational system because of the approximately ten-year decline in flying hours available as well as the number of aircraft in the Air Force inventory. Available measures such as NMCS and Not Mission Capable Maintenance (NMCM) have remained fairly constant in that same time period. Although the simulation results did not reproduce the same numbers portrayed by the actual system, the simulation results reproduced stable behavior. This stable behavior was consistent with actual system behavior. The authors considered this stable behavior along with the research conducted in determining the system structure to be adequate validation of the model. Validation does not mean the model was 100 percent correct. Validation was not a process that ended with the first computer run. Additional research, analysis, and measurement followed by new iterations of the model that would provide a better, more accurate representation of the system structure.

Sensitivity Analysis

As already stated, two different policies were tested using the Operational Reliability Model. The first policy was a 25 percent increase in personnel capability through improved training (3:30). Because more resources

were being expended on training, a 10 percent decrease in supply capability and equipment capability was projected at the same time. Appendix D contained the plots of the simulation run that incorporated this new policy. Table 5-1 is a table showing the percentage change in the measured variables between the old and new policies.

As displayed in Table 5-1, the new policy resulted in only a slight change in aircraft availability and aircraft in maintenance, and aircraft repair rate. A significant difference occurred in the two capability measurements. Repair capability and aircraft maintenance capability decreased by 65.1 percent and 2.26 percent respectively. The aircraft sortie rate remained the same. This seemed to indicate that the policy change had no effect on the Air Force's existing capability to fly sorties but does have a significant effect of the surge capability of the Air Force. Thus, the real significance of this policy change was that the Air Force would continue operating as usual. If increased operations were required as a result of a contingency, the Air Force would have less surge capability.

Changing from three levels of maintenance to two levels of maintenance was the second policy tested in the Operational Reliability Model. In the Air Force, the three levels of maintenance are flight line, intermediate, and depot. The change to two levels would entail eliminating the intermediate level of maintenance at all bases and

TABLE 5-1

PERSONNEL POLICY CHANGE

Variable Name	Initial Run	Personnel Policy Change Run	% Change
Aircraft Available	5780* 6020	5875 6130	1.64 1.83
Aircraft in Maintenance	2820 2570	2735 2470	-3.01 -3.89
Aircraft Repair Rate	2370 2450	2420 2490	2.11 1.63
Sortie Completion Rate	225 325	225 325	0.0 0.0
Repair Capability	0.141 0.129	0.058 0.145	-58.94 -65.12
Aircraft Maintenance Capability	2140 2650	2030 2590	-5.14 -2.26

*The first entry for each variable is the average value for the first three years of the simulation run. The second entry is the last value for the variable obtained after five years.

providing consolidated intermediate-depot maintenance at a number of locations. The locations depend on the using command, the number of bases with a particular aircraft, and the location of these bases. Eliminating the intermediate level of maintenance will result in a considerable savings in personnel. Jones stated that going from three to two levels of maintenance will also result in a savings of spare parts (10:30-32).

To simulate this policy change, the number of personnel in the model was decreased by 40 percent. A 10 percent and 25 percent reduction in supply capability was tested. A required criterion for a two level maintenance operation is increased inherent reliability in the aircraft. To simulate this increase in inherent reliability, the desired level of engineers in the Air Force was increased approximately 30 percent. The plot of these simulation runs are contained in Appendix E. The percentage difference between the old and new policies is contained in Table 5-2.

Again the results showed that the new policies cause only a slight change in aircraft in maintenance, aircraft availability, and the aircraft repair rate. The sortie completion rate remained the same. The significant change occurred in capability factors. Switching from three levels of maintenance to two levels with a 10 percent decrease in supply capability provided a 2.33 percent

TABLE 5-2

THREE TO TWO LEVELS OF MAINTENANCE POLICY CHANGE

Variable Name	Initial Run	10% Decrease in Supply Capability	% Change	25% Decrease in Supply Capability	% Change
Aircraft Available	5780 6020	5705 5900	-1.30 -1.99	5595 5810	-3.20 -3.49
Aircraft in Maintenance	2820 2570	2900 2700	2.84 5.06	3005 2790	6.56 8.56
Aircraft Repair Rate	2370 2450	2335 2400	-1.48 -2.04	2300 2350	-2.95 -4.08
Sortie Completion Rate	225 325	225 325	0.0 0.0	225 325	0.0 0.0
Repair Capability	0.141 0.129	0.140 0.132	-0.71 2.33	0.139 0.129	-1.42 0.0
Aircraft Maintenance Capability	2140 2650	1895 2300	-11.45 -13.21	1550 2000	-27.57 -24.53

increase in the repair capability and a 13.21 percent decrease in aircraft maintenance capability. This different maintenance policy with a 25 percent decrease in supply capability had no change on repair capability and a 24.5 percent decrease in aircraft maintenance capability.

These results indicated that switching from three levels to two levels of maintenance did not have any effect on the current sortie completion rate. This policy change would probably not have any immediate effect on the operational reliability of the system. The less obvious effect was that the capability of the Air Force would be decreased.

Conclusions

Policy Modeling Conclusions

A system dynamics model of operational reliability was constructed and used to experiment with policy changes. These system experiments indicated that the system under study tended to exhibit stable behavior. Two performance measures, repair capability and aircraft maintenance capability, attempted to provide a method to determine the available capability of the Air Force. Both of these measures changed slightly when the policy changes were tested in the model. The data to determine these measures of capability are not currently available in the Air Force. A method to determine these measures was derived from the research conducted in preparing this thesis.

In determining the model structure, a review of the literature concerning reliability and the discussions with individuals knowledgable in the system were conducted. It appeared that many managers had an intuitive feeling of the Air Force's capability. The amount of detail contained within that intuitive feeling is probably proportional to the management level in the system where the manager operated. The top level policy maker might have a good intuitive grasp of the total Air Force capability, but have a poor understanding of a single squadron's capability. The opposite would probably be true of the manager in charge of a base-level maintenance squadron for a particular aircraft.

This intuitive feeling of capability possessed by these managers must be examined, and a quantitative measure must be developed. To begin to measure and define the capability of the Air Force requires a concerted effort to capture the knowledge possessed by the personnel at the working level of the system which provides them with this intuitive feeling. Merely asking these people how they determine their own capability would not be sufficient. A long-term research effort conducted by a multi-disciplinary group would probably be required. This group would have to investigate and determine those system parameters and their relationships that the working level managers use to determine their capability. This would be the starting

point from which measures for Air Force total capability could be determined.

Operational Reliability Model Summary

The main objective of this research was to develop a computer simulation model of the reliability of aircraft weapon systems. This objective was met. The specific objectives of this research were also fulfilled. The causal loop diagrams developed in Chapter III, identified the most important internal and external forces affecting the reliability system. These causal loops also identified the significant cause effect relationships and information feedback loops connecting the internal and external forces. A structural model and mathematical equations for a computer simulation were constructed in Chapter IV. This Operational Reliability Model represented the forces, information flows, and decision policies of the reliability system.

Examples of different management policies and how these policies affect reliability were identified in this chapter. The model exhibited relative stability when the policy changes were tested. This stable behavior of the reliability model was similar to the behavior of the system being tested. In this chapter, capability was demonstrated to be closely related to reliability. At that time it was pointed out that the Air Force currently does not have well defined measures of the total capability of aircraft weapon

systems. Air Force capability was identified as an area requiring additional research. After measures for the Air Force's capability have been developed, new data collection systems will be required to capture this information. The last objective was to provide an improved conceptualization of reliability for other researchers to build upon. It is hoped that this objective was fulfilled along with the other objectives.

Satisfying the research objectives provided the answers to the research questions. Chapters III and IV identified the relationships between reliability and other components of the system which affected the reliability of an aircraft weapon system. A conceptual model of reliability was developed and used as the basis for the mathematical computer simulation model. Finally, the use of the model as a tool for policy makers was demonstrated in Chapter V.

The authors feel a final word on system dymamics is needed. The technique used in system dynamics modeling was deceptively simple. The actual use of the system dynamics paradigm from conceptualization through computerization of the model was mentally demanding. It forced a continual re-evaluation of the actual structure of the system being modeled. The question, "Is a particular variable relevant to system behavior?", was always in the forefront of the model design effort.

The total research effort to prepare this thesis has been rewarding. A concept of operational reliability being closely related to total capability of the Air Force was developed. A computer simulation model was designed around this concept of operational reliability. Constructing the model and using it to explore policy changes provided insights into the reliability system. It is hoped that this thesis assists others in developing similar insights and leads to a better understanding of reliability.

APPENDICES

APPENDIX A

OPERATIONAL RELIABILITY MODEL LISTING

```
1000*     OPERATIONAL RELIABILITY MODEL
1010NOTE
1020      MAINTENANCE SECTOR
1030NOTE
1040L     AA.K=AA.J+DT*(ARR.JK-AIMR.JK)
1050N     AA=AAI
1060C     AAI=6020
1070           AA - AIRCRAFT AVAILABILITY (AIRCRAFT)
1080           ARR - AIRCRAFT REPAIR RATE (AIRCRAFT/DAY)
1090           AIMR - AIRCRAFT INTO MAINTENANCE RATE (AIRCRAFT/DAY)
1100NOTE
1110L     AM.K=AM.J+DT*(AIMR.JK-ARR.JK)
1120N     AM=AMI
1130C     AMI=2500
1140           AM - AIRCRAFT IN MAINTENANCE (AIRCRAFT)
1150           AIMR - AIRCRAFT INTO MAINTENANCE RATE (AIRCRAFT/DAY)
1160           ARR - AIRCRAFT REPAIR RATE (AIRCRAFT/DAY)
1170NOTE
1180R     AIMR.KL=AA.K*SMF+UMF.K*SCR.JK
1190A     UMF.K=UMC-IR.K
1200C     UMC=.3
1210C     SMF=.4
1220           AIMR - AIRCRAFT INTO MAINTENANCE RATE (AIRCRAFT/DAY)
1230           AA - AIRCRAFT AVAILABILITY (AIRCRAFT)
1240           UMF - UNSCHEDULED MAINTENANCE FACTOR (AIRCRAFT/SORTIE)
1250           SMF - SCHEDULED MAINTENANCE FACTOR (PERCENT/AIRCRAFT)
1260           SCR - SORTIE COMPLETION RATE (SORTIE/DAY)
1270NOTE
1280R     ARR.KL=DELAY3(AR.K,MDEL)
1290A     AR.K=ARF.K*AM.K
1300A     ARF.K=(PC.K+SC.K+EC.K+FC.K)/100
1310C     MDEL=10
1320           ARR - AIRCRAFT REPAIR RATE (AIRCRAFT/DAY)
1330           AR - AIRCRAFT REPAIR (AIRCRAFT/DAY)
1340           ARF - AIRCRAFT REPAIR FACTOR (PERCENT/AIRCRAFT)
1350           AM - AIRCRAFT IN MAINTENANCE (AIRCRAFT)
1360           PC - PERSONNEL CAPABILITY (PERCENT/AIRCRAFT)
1370           SC - SUPPLY CAPABILITY (PERCENT/AIRCRAFT)
1380           EC - EQUIPMENT CAPABILITY (PERCENT/AIRCRAFT)
1390           FC - FACILITY CAPABILITY (PERCENT/AIRCRAFT)
1400           MDEL - MAINTENANCE DELAY (DAYS)
1410NOTE
1420A     PC.K=TABHL(PCT,AM.K,0,8600,1075)*PRMN.K
1430T     PCT=40/38/36/34/32/30/28/25/23
1440A     PRMN.K=TABHL(PRMNT,PPA.K,0,.5,.1)
1450T     PRMNT=.8/.88/.96/1.04/1.12/1.2
1460A     PPA.K=(PERCP.K/MAIN.K)*(PERS/TAC)
1470A     PERCP.K=TABHL(PERCPT,MAIN.K,0,1,.2)
1480T     PERCPT=0/.001/.004/.009/.016/.025
1490A     MAIN.K=TABHL(MAINT,TECH.K,0,1,.1)
1500T     MAINT=.001/.02/.03/.04/.06/.08/.1/.15/.2/.4/1.0
```

```
1510C    PERS=175E3
1520C    TAC=0600
1530         PC - PERSONNEL CAPABILITY (PERCENT/AIRCRAFT)
1540         PRRM - PERSONNEL REPAIR RATE MULTIPLIER (DIMENSIONLESS)
1550         PCT - PERSONNEL CAPABILITY TABLE (PERCENT AIRCRAFT)
1560         PPA - PERSONNEL PER AIRCRAFT (DIMENSIONLESS)
1570         PERCP - PERSONNEL CAPACITY (MAINTENANCE ACTIONS/PERSONNEL)
1580         PERCPT - PERSONNEL CAPACITY TABLE (MAINT ACTS/PERSONNEL)
1590         MAIN - MAINTAINABILITY (MAINTENANCE ACTIONS/AIRCRAFT)
1600         MAINT - MAINTAINABILITY TABLE (MAINT ACTS/AIRCRAFT)
1610         PERS - PERSONNEL
1620         TAC - TOTAL AIRCRAFT
1630NOTE
1640A    EC.K=TABHL(ECT,AN.K,0,0600,1975)*ERRM.K
1650T    ECT=15/14/13/12.5/12/11/10.5/10/9
1660A    ERRM.K=TABHL(ERRMT,TECH.K,0,1,.1)
1670T    ERRMT=1/1.05/1.1/1.15/1.2/1.25/1.3/1.35/1.4/1.45/1.5
1680         EC - EQUIPMENT CAPABILITY (PERCENT/AIRCRAFT)
1690         ECT - EQUIPMENT CAPABILITY TABLE (PERCENT/AIRCRAFT)
1700         ERRM - EQUIPMENT REPAIR RATE MULTIPLIER (DIMENSIONLESS)
1710         ERRMT - EQUIP REPAIR RATE MULT TABLE (DIMENSIONLESS)
1720         TECH - TECHNOLOGY
1730NOTE
1740A    SC.K=TABHL(SCT,AN.K,0,0600,1075)
1750T    SCT=30/28/27/25/24/22/20/19/17
1760A    FC.K=TABHL(FCT,AN.K,0,0600,1075)
1770T    FCT=15/14/13/12.5/12/11/10.5/10/9
1780         SC - SUPPLY CAPABILITY (PERCENT/AIRCRAFT)
1790         SCT - SUPPLY CAPABILITY TABLE (PERCENT/AIRCRAFT)
1800         FC - FACILITY CAPABILITY (PERCENT/AIRCRAFT)
1810         FCT - FACILITY CAPABILITY (PERCENT/AIRCRAFT)
1820NOTE
1830     OPERATIONS SECTOR
1840NOTE
1850L    FHA.K=FHA.J-FHU.J+PULSE(PH,364,364)+PULSE(PH1,273,364)
1860N    FHA=FHAI
1870C    FHAI=20E5
1880C    PH=20E5
1890C    PH1=15E4
1900         FHA - FLYING HOURS AVAILABLE (HOURS/YEAR)
1910         FHAI - FLYING HOURS INITIALLY (HOURS/YEAR)
1920         FHU - FLYING HOURS USED (HOURS)
1930         PH - PULSE HEIGHT (HOURS/YEAR)
1940         PH1 - PULSE HEIGHT 1 (HOURS/YEAR)
1950NOTE
1960A    FHU.K=SCR.JK*SL
1970C    SL=3.5
1980         FHU - FLYING HOURS USED (HOURS/DAY)
1990         SCR - SORTIE COMPLETION RATE (SORTIES/DAY)
2000         SL - SORTIE LENGTH (HOURS/SORTIE)
```

```
2010NOTE
2020L    CA.K=CA.J+DT*(CTR.JK-CAR.JK)
2030N    CA=CAI
2040N    CAI=CR*TAC
2050C    CR=2.0
2060         CA - CREW AVAILABILITY (CREWS)
2070         CAI - CREWS AVAILABLE INITIALLY (CREWS)
2080         CR - CREW RATIO (CREWS/AIRCRAFT)
2090         TAC - TOTAL AIRCRAFT (AIRCRAFT)
2100         CTR - CREW TRAINING RATE (CREWS/DAY)
2110         CAR - CREW ATTRITION RATE (CREWS/DAY)
2120NOTE
2130R    CTR.KL=(CAI+(AMP*SIN(6.283*TIME.K/CPER)))/DT
2140C    AMP=.25
2150C    CPER=1820     5 YEARS
2160         CTR - CREW TRAINING RATE (CREWS/DAY)
2170         CAI - CREWS AVAILABLE INITIALLY (CREWS)
2180         AMP - AMPLITUDE OF SINE INPUT (DIMENSIONLESS)
2190         TIME - SIMULATION TIME CLOCK (DAYS)
2200         CPER - PERIOD OF SINE INPUT ( DAYS)
2210NOTE
2220R    CAR.KL=CA.K/CDEL
2230C    CDEL=1456     4 YEARS
2240         CAR - CREW ATTRITION RATE (CREWS/DAY)
2250         CA - CREW AVAILABILITY (CREWS)
2260         CDEL - CREW DELAY (DAYS)
2270NOTE
2280L    SS.K=SS.J+DT*(SSR.JK)+PULSE(-SS.J,364,364)
2290N    SS=SSI
2300C    SSI=0
2310         SS - SCHEDULED SORTIES (SORTIES)
2320         SSI - SCHEDULED SORTIES INITIALLY (SORTIES)
2330         SSR - SCHEDULED SORTIE RATE (SORTIES/DAY)
2340NOTE
2350R    SSR.KL=AGA.K
2360A    AGA.K=CLIP(LBGA.K,CA.K,CA.K,LBSA.K)
2370A    LBGA.K=CLIP(NGA.K,AA.K,AA.K,NGA.K)
2380A    NGA.K=((FMA.K/SL)/(365-YTIN.K))*DT
2390L    YTIN.K=CLIP(0,YTIN.J,YTIN.J,364)+DT
2400N    YTIN=0
2410         SSR - SCHEDULED SORTIE RATE (SORTIES/DAY)
2420         AGA - AVAILABLE SCHEDULED AIRCRAFT (SORTIES/DAY)
2430         LBGA - LIMIT BETWEEN SORTIES/AIRCRAFT (SORTIES/DAY)
2440         NGA - NUMBER SORTIES AVAILABLE (SORTIES/DAY)
2450         YTIN - YEARS TIME
2460NOTE
2470L    SUCS.K=SUCS.J+DT*(SCR.JK)+PULSE(-SUCS.J,364,364)
2480N    SUCS=SUCSI
2490C    SUCSI=0
2500         SUCS - SUCCESFUL SORTIES (SORTIES)
```

```
2510         SUCSI - SUCCESSFUL SORTIES INITIALLY (SORTIES)
2520         SCR - SORTIE COMPLETION RATE (SORTIES/DAY)
2530NOTE
2540R     SCR.KL=SSR.JK*SCRF.K
2550A     SCRF.K=1-NORMRN(SA,SD)*IRM.K
2560C     SA=.04
2570C     SD=.02
2580         SCR - SORTIE COMPLETION RATE (SORTIES/DAY)
2590         SSR - SCHEDULED SORTIE RATE (SORTIES/DAY)
2600         SCRF - SORTIE COMPLETION RATE FACTOR (DIMENSIONLESS)
2610         SA - SORTIE ABORT MEAN (DIMENSIONLESS)
2620         SD - STANDARD DEVIATION
2630NOTE
2640      RESEARCH AND DEVELOPMENT SECTOR
2650NOTE
2660L     NE.K=NE.J+DT*(HR.JK-EER.JK)
2670N     NE=NEI
2680C     NEI=200
2690         NE - NEW ENGINEERS
2700         NEI - NEW ENGINEERS INITIALLY (ENGINEERS)
2710NOTE
2720R     HR.KL=HRF.K
2730A     HRF.K=(DLE.K-NE.K)/HRD
2740C     HRD=720     2 YEARS
2750         HR - HIRING RATE (ENGINEERS/DAY)
2760         HRF - HIRING RATE FACTOR (ENGINEERS/DAY)
2770         DLE - DESIRED LEVEL OF ENGINEERS (ENGINEERS)
2780         NE - NEW ENGINEERS
2790         HRD - HIRING RATE DELAY (DAYS)
2800NOTE
2810A     DLE.K=TABHL(DLET,SAM.K,0,8600,1075)*IRN.K
2820T     DLET=0/650/760/830/890/950/1000/1000/1000
2830A     SAM.K=SMOOTH(AM.K,364)
2840         DLE - DESIRED LEVEL OF ENGINEERS (ENGINEERS)
2850         DLET - DESIRED LEV ENGINEERS TABLE (ENGINEERS)
2860         SAM - SMOOTHED AIRCRAFT IN MAINTENANCE (AIRCRAFT)
2870NOTE
2880R     EER.KL=NE.K/EDEL
2890C     EDEL=720     2 YEARS
2900         EER - EXPERIENCED ENGINEER RATE (ENGINEERS)
2910         EDEL - EXPERIENCE DELAY (DAYS)
2920NOTE
2930L     EE.K=EE.J+DT*(EER.JK-EAR.JK)
2940N     EE=EEI
2950C     EEI=200
2960         EE - EXPERIENCED ENGINEERS (ENGINEERS)
2970         EEI - EXPERIENCED ENGINEERS INITIALLY (ENGINEERS)
2980         EER - EXPERIENCED ENGINEERS RATE (ENGINEERS/DAY)
2990         EAR - ENGINEER ATTRITION RATE (ENGINEERS/DAY)
3000NOTE
```

```
3010R     EAR.KL=EE.K/ADEL
3020C     ADEL=3640      10 YEARS
3030          EAR - ENGINEER ATTRITION RATE (ENGINEERS/DAY)
3040          EE - EXPERIENCED ENGINEERS (ENGINEERS)
3050          ADEL - ATTRITION DELAY (DAYS)
3060NOTE
3070A     IR.K=TABHL(IRT,TECH.K,0,1.0,.25)
3080T     IRT=.01/.015/.04/.1/.2
3090A     IRM.K=1-IR.K
3100A     TECH.K=TABHL(TECHT,EE.K,0,1000,100)
3110T     TECHT=0/.04/.08/.11/.14/.2/.8/.9/.94/.98/1
3120          IR - INHERENT RELIABILITY (DIMENSIONLESS)
3130          IRT - INHERENT RELIABILITY TABLE (DIMENSIONLESS)
3140          IRM - INHERENT RELIABILITY MULTIPLIER (DIMENSIONLESS)
3150          TECH - TECHNOLOGY   (DIMENSIONLESS)
3160          TECHT - TECHNOLOGY TABLE (DIMENSIONLESS)
3170          EE - EXPERIENCED ENGINEERS (ENGINEERS)
3270NOTE
3280          JOB CONTROL STATEMENTS
3290SPEC   DT=.1,PLTPER=36.4,LENGTH=1820
3300PLOT   FNA=F/AA=A/AH=H/ARR=R
3310PLOT   SCR=S/RCAP=0/ACAP=0
3320RUN
```

APPENDIX B

DERIVATION OF REPAIR CAPABILITY AND AIRCRAFT MAINTENANCE CAPABILITY EQUATIONS

Two supplementary equations were formulated as an attempt to measure the additional capability that exists in the operational reliability system. The equations determine the total personnel, supply, equipment, and facility capability availability. The terms in the equations are adjustment factors, determining the increased capability provided by the Research and Development sector. The capability requested to generate the system was then subtracted from this total capability. The result is the additional capability available. The equations are:

RCAP.K=((100+(PC.K-PC.K/PRRM.K)+
(EC.K-EC.K/ERRM.K)/100)-ARF.K

ACAP.K=5000+AM.K*(((PC.K-PC.K/PRRM.K)+
(EC.K-EC.K/ERRM.K))/100-1)

When policy changes were tested in the model, additional adjustments were required to compensate for the 10 percent and 25 percent decreases in supply capability. These equations are:

<u>10 Percent Decreace in Supply Capability</u>

RCAP.K=((97+PC.K-PC.K/PRRM.K)+
(EC.K-EC.K/ERRM.K))/100)-ARF.K

ACAP.K=4850+AM.K*(((PC.K-PC.K/PRRM.K)+

(EC.K-EC.K/ERRM.K))/100-1)

<u>25 Percent Decrease in Supply Capability</u>

RCAP.K=((92.5+PC.K-PC.K/PRRM.K)+

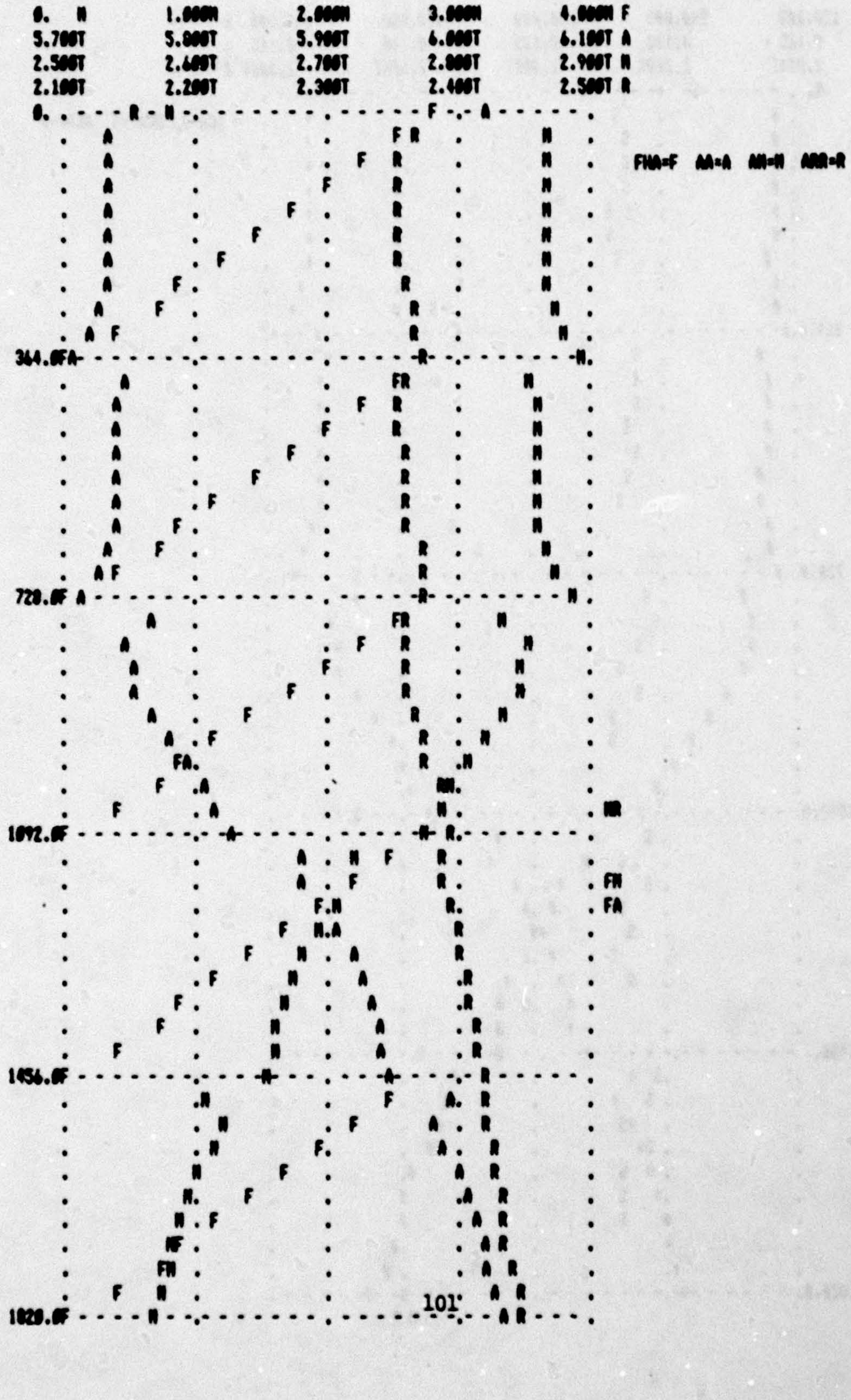
(EC.K-EC.K/ERRM.K))/100)-ARF.K

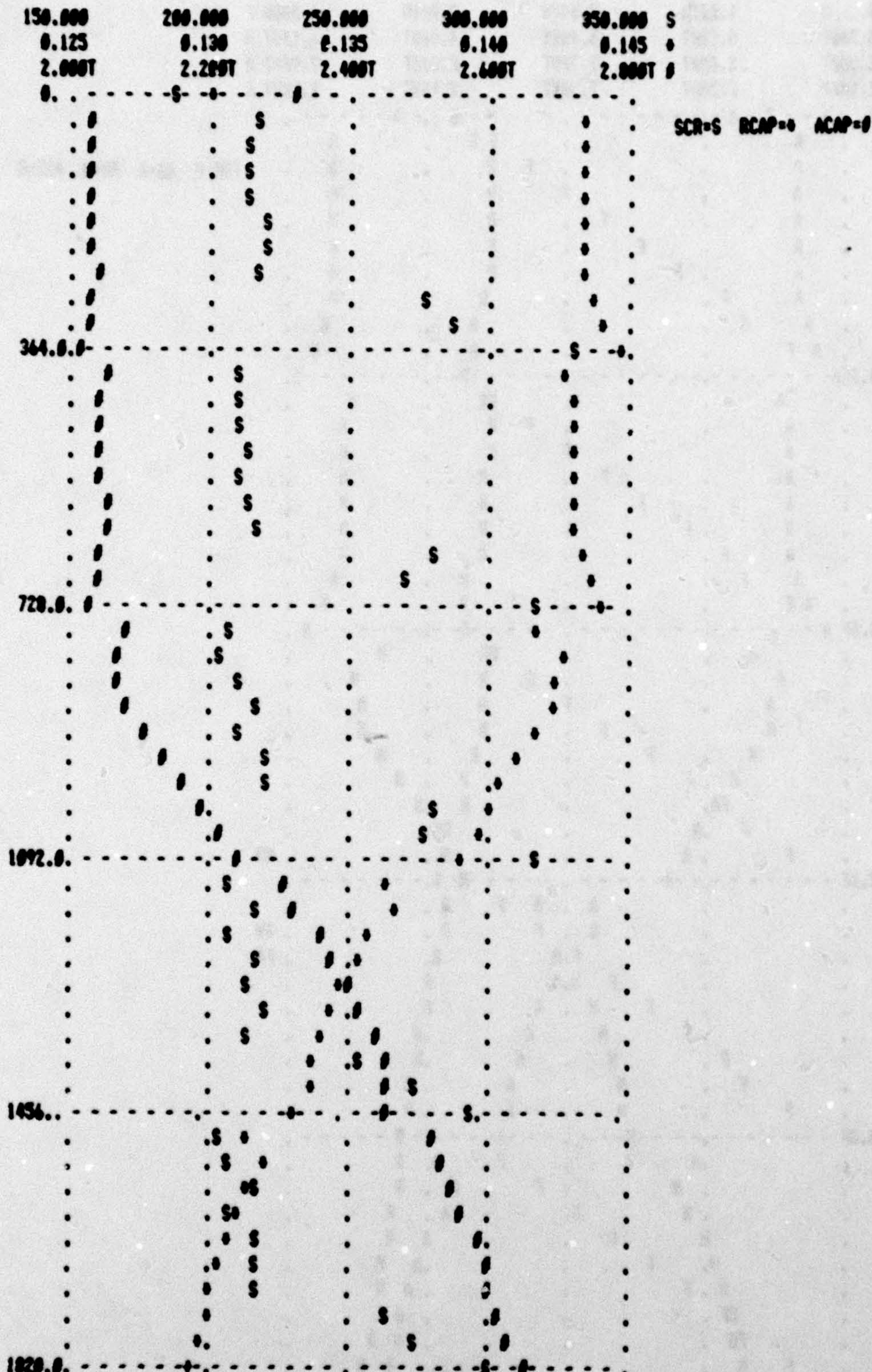
ACAP.K=4625+AM.K*(((PC.K-PC.K/PRRM.K)+

(EC.K-EC.K/ERRM.K))/100-1)

APPENDIX C

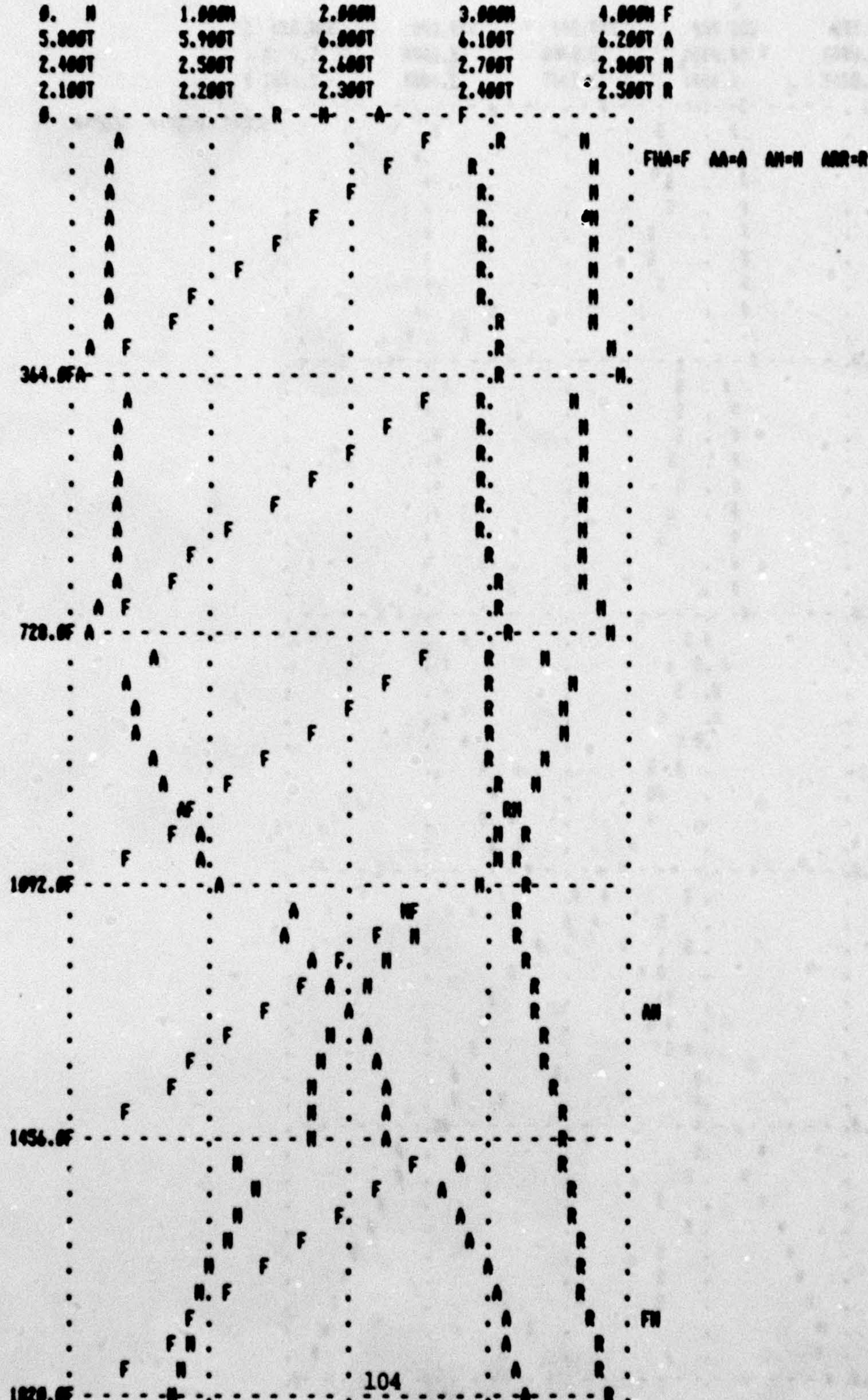
INITIAL SIMULATION RUN

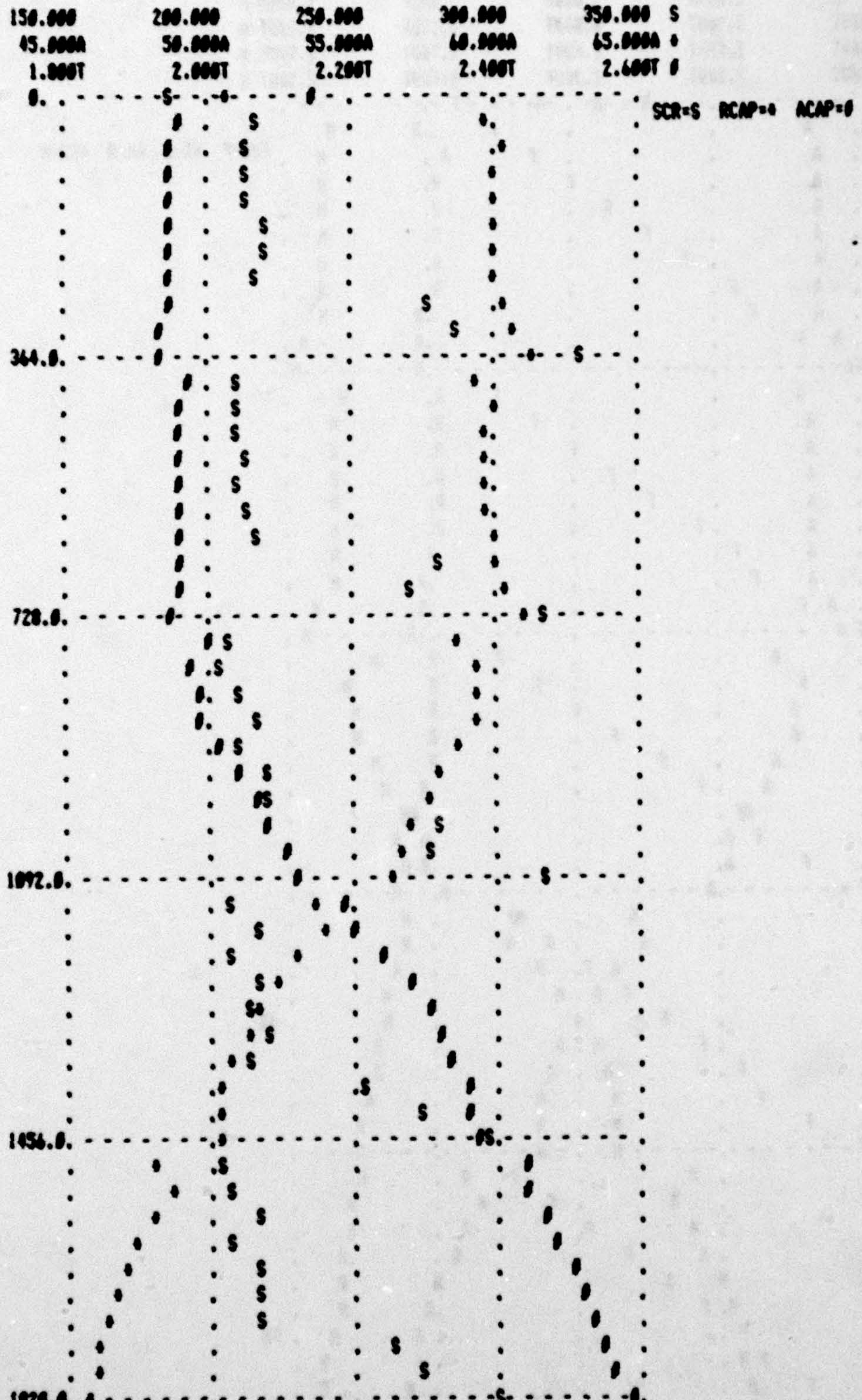

0. M 1.000M 2.000M 3.000M 4.000M F
5.700T 5.800T 5.900T 6.000T 6.100T A
2.500T 2.600T 2.700T 2.800T 2.900T M
2.100T 2.200T 2.300T 2.400T 2.500T R
0.
364.0F
728.0F
1092.0F
1456.0F
1820.0F
FMA=F AA=A AM=M ARR=R


150.000 200.000 250.000 300.000 350.000 S
0.125 0.130 0.135 0.140 0.145 *
2.000T 2.200T 2.400T 2.600T 2.800T #
0.
364.0
728.0
1092.0
1456.
1820.0
SCR=S RCAP=* ACAP=#

APPENDIX D

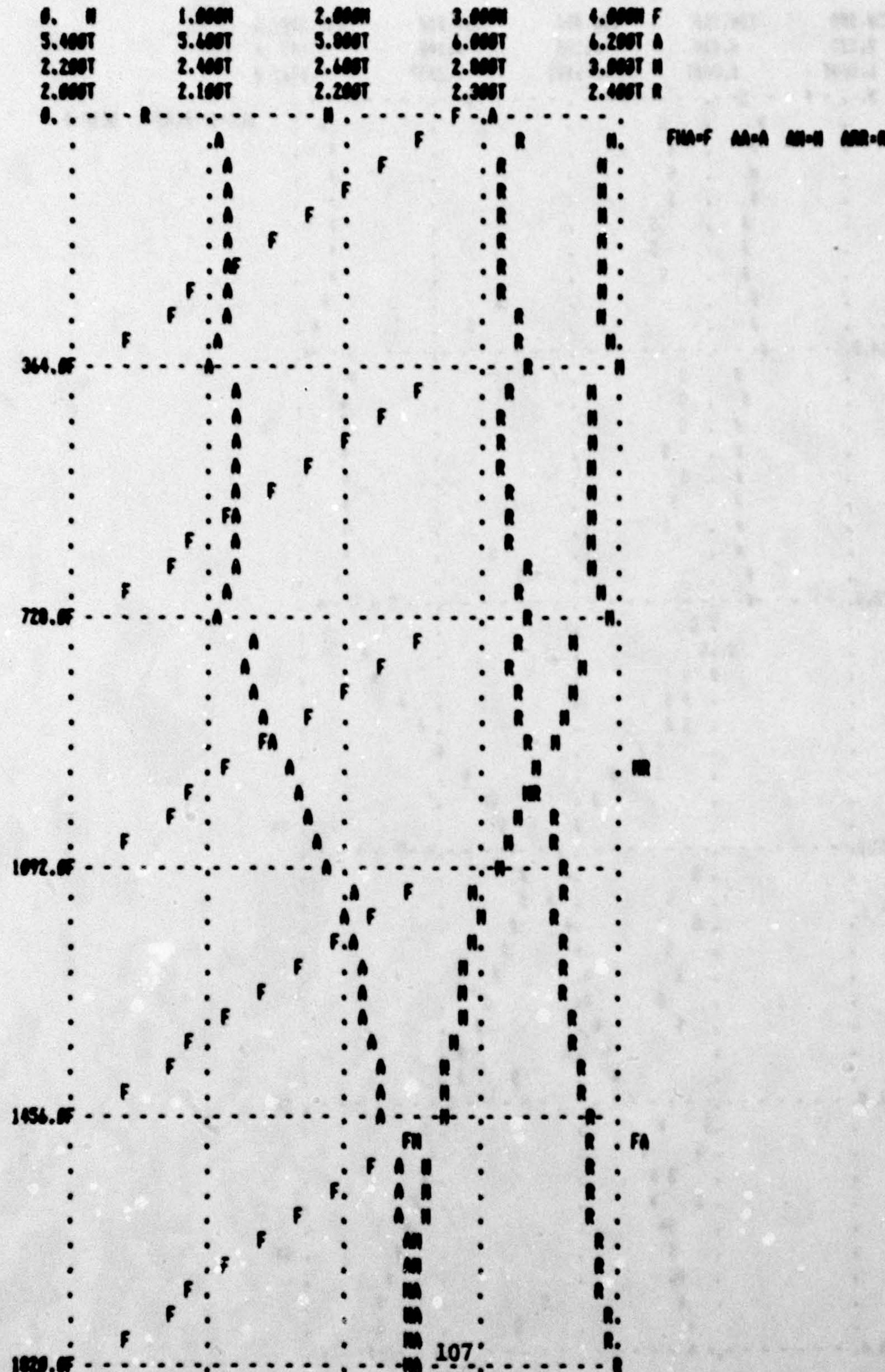
PERSONNEL POLICY CHANGE

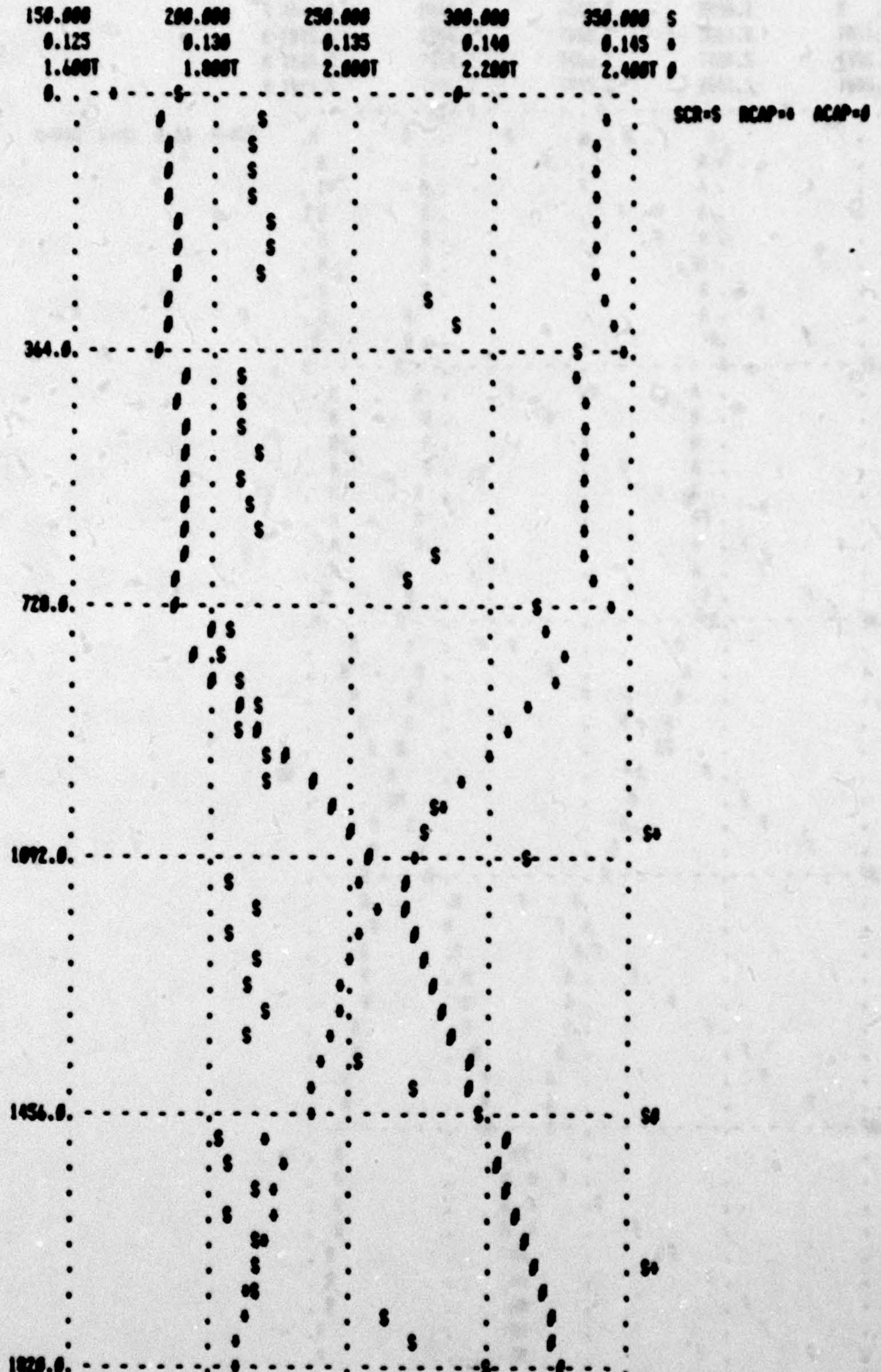

0. M 1.000M 2.000M 3.000M 4.000M F
5.000T 5.900T 6.000T 6.100T 6.200T A
2.400T 2.500T 2.600T 2.700T 2.800T M
2.100T 2.200T 2.300T 2.400T 2.500T R
FHA=F AA=A AM=M ABR=R
364.0F
728.0F
1092.0F
1456.0F
1820.0F
AM
FM

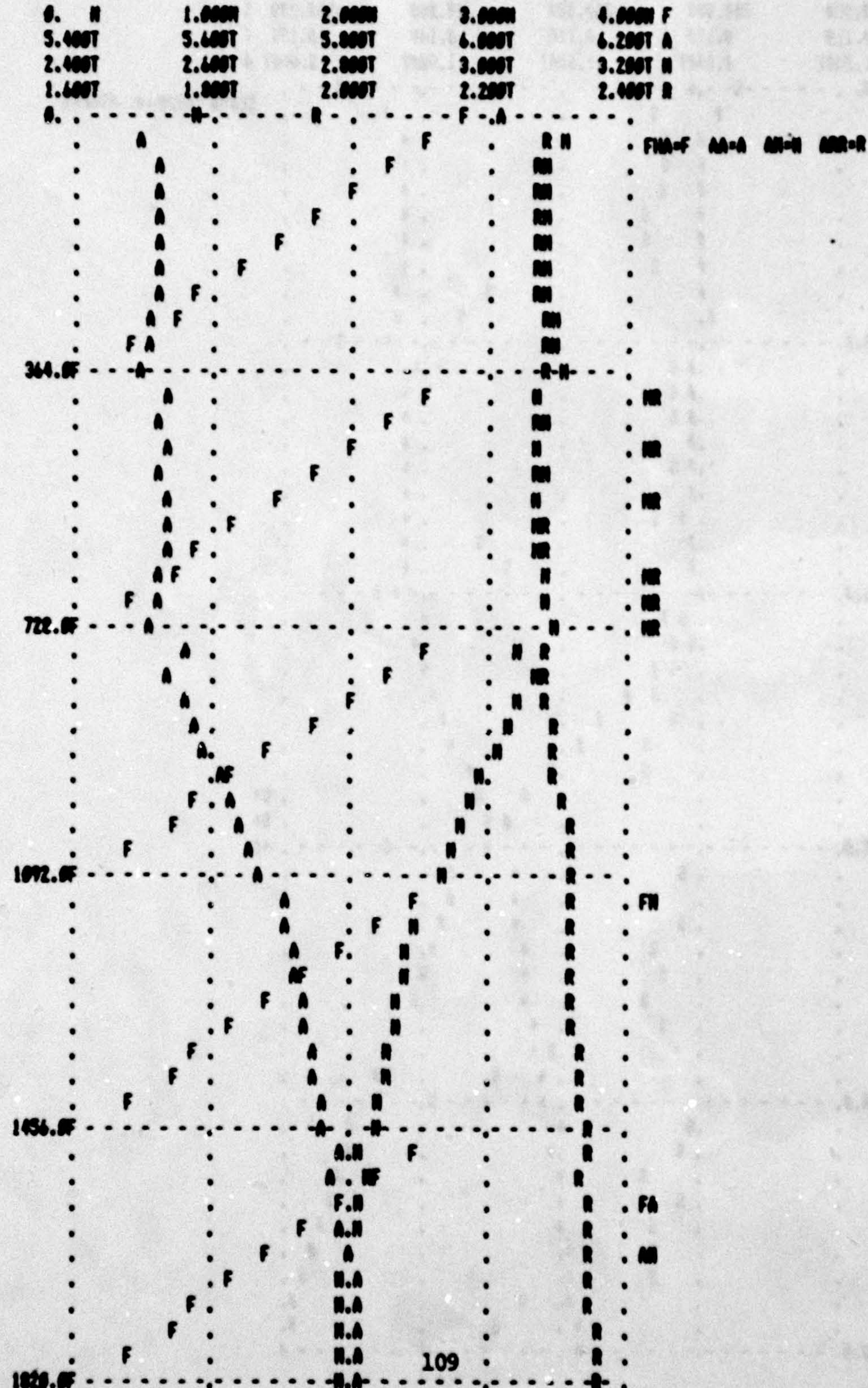

150.000 200.000 250.000 300.000 350.000 S
45.000A 50.000A 55.000A 60.000A 65.000A +
1.000T 2.000T 2.200T 2.400T 2.600T #
SCR=S RCAP=+ ACAP=#
0.
364.0
728.0
1092.0
1456.0
1820.0

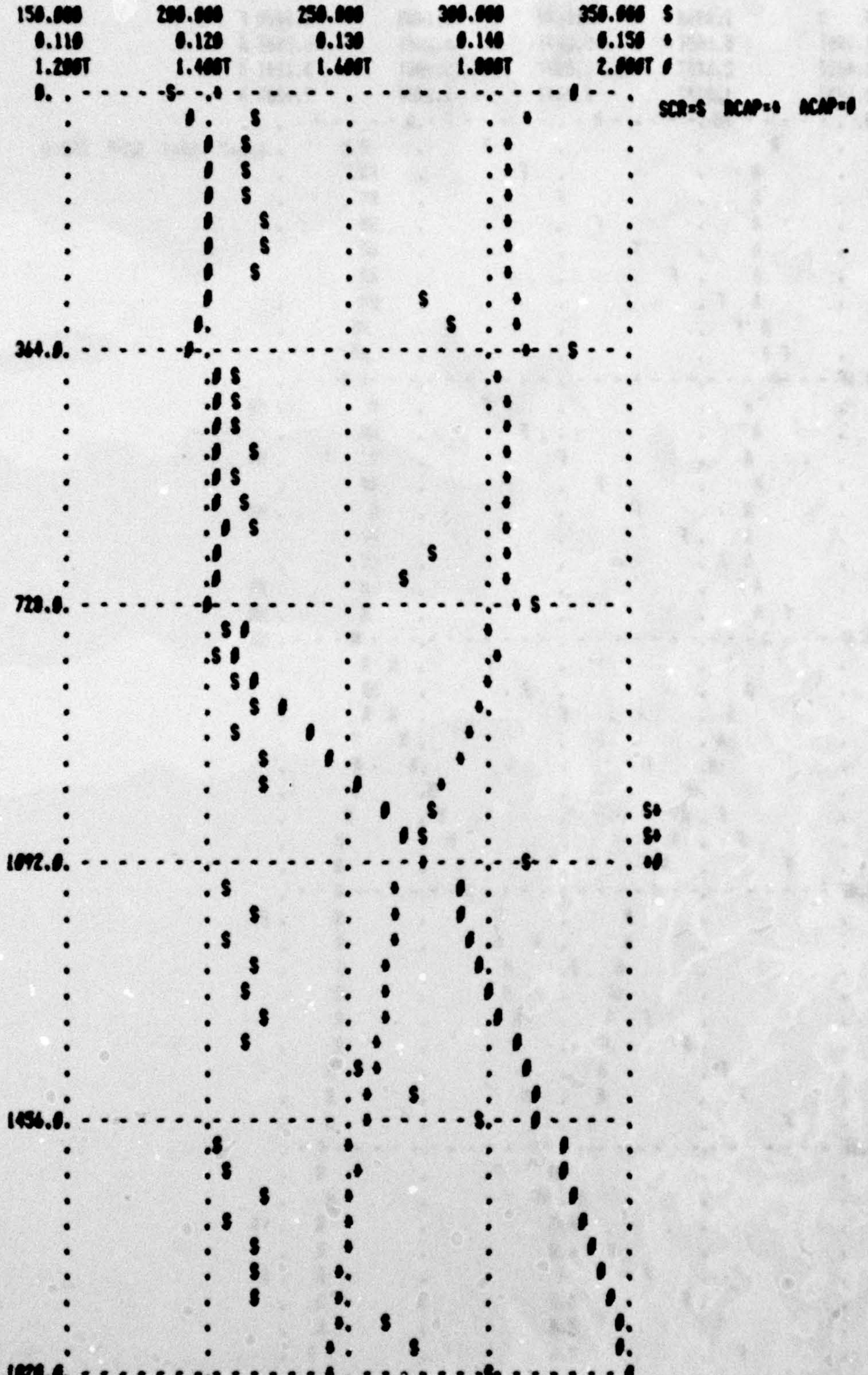
APPENDIX E

THREE TO TWO LEVELS OF MAINTENANCE
POLICY CHANGE


0. N 1.000N 2.000N 3.000N 4.000N F
5.400T 5.600T 5.800T 6.000T 6.200T A
2.200T 2.400T 2.600T 2.800T 3.000T N
2.000T 2.100T 2.200T 2.300T 2.400T R
FNA=F AA=A AN=N ADR=R
0.
364.0F
720.0F
1092.0F
1456.0F
1820.0F


150.000 200.000 250.000 300.000 350.000 S
0.125 0.130 0.135 0.140 0.145 *
1.600T 1.800T 2.000T 2.200T 2.400T 0
SCR=S BCAP=* ACAP=0
0.
364.0
728.0
1092.0
1456.0
1820.0


0. N 1.000N 2.000N 3.000N 4.000N F
5.400T 5.600T 5.800T 6.000T 6.200T A
2.400T 2.600T 2.800T 3.000T 3.200T N
1.600T 1.800T 2.000T 2.200T 2.400T R
364.0F
722.0F
1092.0F
1456.0F
1820.0F


150.000 200.000 250.000 300.000 350.000 S
0.110 0.120 0.130 0.140 0.150 +
1.200T 1.400T 1.600T 1.800T 2.000T 0
SCR=S RCAP=+ ACAP=0
0.
364.0
728.0
1092.0
1456.0
1820.0

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